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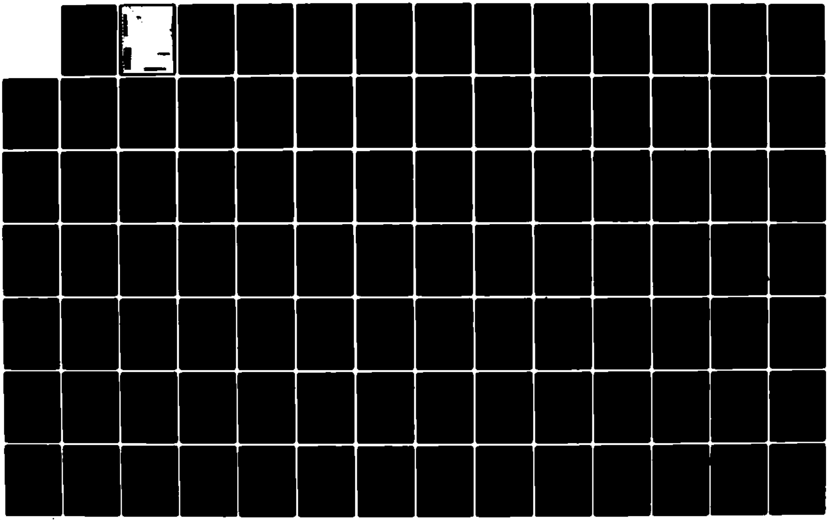

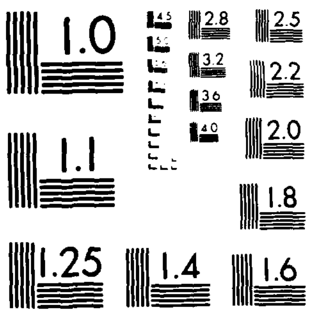

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The filament winding of a ship hull 150 ft. long was studied to define the problems and possible solutions associated with this method of manufacturing a ship hull out of Glass Reinforced Plastic (GRP). Winding machine and mandrel concepts were reviewed, as well as structural requirements and possible materials. A design of a 1/5 scale (30 ft.) hull and mandrel was developed, and recommendations made as to tasks that would need to be undertaken to successfully build such a model, and eventually a ship.

SUMMARY

The filamant winding of a ship hull 150 ft long was studied to define the problems and possible solutions associated with this method of manufacturing a hull out of glass reinforced plastic (GRP). Winding machine and mandrel concepts were reviewed, as well as the structural requirements and possible materials. A design of a 1/5th scale (30 ft) model hull and winding mandrel or mold was developed. Recommendations were made as to tasks that would need to be undertaken to successfully build such a model, and eventually a ship, using these methods.

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PREFACE

This report was prepared under Contract No. N00014-83-C-2031. The study was sponsored by Dr. H. H. Vanderveldt, Naval Sea Systems Command (SEA 05R25). It was funded under MATERIALS TECHNOLOGY PROGRAM ELEMENT 62761N. The encouragement and support of Mr. J. J. Kelly (Office of Naval Technology) is greatly appreciated. The contract was administered by the Naval Research Laboratory; Dr. Irvin Wolock (NRL 6383) was the Technical Monitor.

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SECTION 1
INTRODUCTION

This section describes the purpose of the contract, the general state-of the art in filament winding at the time of the investigation, and the general state-of-the-art in GRP (Glass Reinforced Plastic) shipbuilding using non-filament wound methods. This information provides the starting point for the investigation of the proposed filament winding of a 30 ft long model of a 150 ft minesweeper hull, in order to demonstrate the feasibility and techniques of winding a shape such as a ship hull.

1.1 PURPOSE OF THE CONTRACT

In a previous contract undertaken by McClean Anderson, Inc., a manufacturer of filament winding machinery, a small (4.2 ft) model of a 200 ft minesweeper hull was fabricated on filament winding machinery, demonstrating that a shape like that of a ship hull could be wound using these techniques.[1-1] This model design was based on a simplified structural analysis, and assumed fiber orientations of 0,+45,-45,& 90 degrees. Fiber paths were determined experimentally to allow continuous winding, and were not documented except in the winding machine memory.

The results of that study and model fabrication were sufficiently encouraging so that the present study was undertaken. The specific objective of this contract was to develope the design of a 1/5 scale model of a 150 ft LOA (length over all) minesweeper hull, and at the same time to identify the specific problems associated with scaling the winding of the model up to a full scale ship hull. In addition to identification of required winding paths and techniques, the materials to be used and the basis

for their selection was to be specified.

In conjuction with the model design, a preliminary design was prepared for the mandrel required to accomplish the winding, and the implications of scaling this mandrel concept up to ship scale were investigated. The cost of modifying current winding machinery to accomodate the model winding was also investigated, and various possibilities for the design of a machine capable of winding a 200 ft ship hull were explored.

Finally, conclusions and recommendations for a program to achieve the winding of such a hull were developed.

1.2 FILAMENT WINDING STATE-OF-THE-ART

Over a period of many years, filament winding has developed from its beginnings in pipe fabrication to a broad variety of applications. Proven products include complex iso-grid structural shapes, large axi-symmetric pressure vessels, large non-uniform shapes such as railroad hopper cars, and smaller irregular shapes such as vehicle springs.[1-1] The Trident and MX missiles both use filament wound sections in their motor casings.

1.2.1 Advantages of Filament Winding

The major advantages which recommend filament winding over current hand layup methods are the reduced manhours per pound of fabricated structure, the higher glass reinforcement percentage in the wound structure, and the resulting higher structural performance and fire resistance of the filament wound structure. The cost of the mandrel required for filament winding is expected to be somewhat higher than the cost of a mold for hand or semi-automatic layup, primarily due to its structural requirements. It is anticipated, however, that the labor saving resulting from

machine winding of the hull will more than compensate for the additional mold cost, just as the cost of the mold for multiple hand layup hulls is more than offset by the cost savings compared to one-off hull construction and finishing. It should be noted that a filament wound hull will have a less smooth outer surface than a female molded hull, and the cost of finishing this surface to an acceptable fairness will reduce the savings in fabrication manhours by some yet undetermined amount. These relative costs are typical of the issues which can be further clarified by building the 30 ft model as proposed for the next phase of this program.

1.2.2 Winding Non-axisymmetric Shapes

Current filament winding techniques generally rely on selection of stable or non-slipping fiber paths, where the bands of fibers are laid down in such a way that there is no tendency for the tension in the fibers to pull them out of position before the matrix cures. This requirement results in the selection of fiber paths that may not be optimum for structural purposes, and as the shape becomes more irregular, the restrictions on these fiber paths become more important. This problem becomes most noticable at the deck edge, bow, and stern of a ship hull shape, and was a principal concern in the current study. An additional problem is the tendency of fibers under tension to "bridge" across hollows such as the bow flare and the sheer in the weather deck, and this was also addressed in the current contract.

1.2.3 Materials for Filament Winding

In the materials area, resins for filament winding are generally less viscous than those used in hand layup, in order to assure adequate flow and wetting of the fibers as they are impregnated in the winding machine. The cure cycles currently used in fila-

ment winding are generally based on thinner sections than those envisioned for a ship hull, although some .ork has been done on pipe and spring sections over 1 inch in thickness. The sections required for a monocoque ship hull will be significantly thicker, up to several inches, and would require a well controlled cure cycle to limit exotherm problems and provide adequate pimary bonding to underlying layers.

1.3 GRP SHIPBUILDING STATE-OF-THE-ART

Since Glass Reinforced Plastic (GRP) or Fiber Reinforced Plastic (FRP) were first used in boat hulls over 30 years ago, many advances have been made in both the resin and reinforcement materials and the techniques for building molds and fabricating the required parts. The major limitations with regard to ship size have derived mainly from the low flexural modulus of GRP, rather than its strength, and from cost and quality control problems related the hand fabrication and curing cycles of the GRP materials. As the ship size increases to the point where steel is a competitive option, the problems of GRP cost and structural stiffness become more pronounced. That is one reason why mine warfare ships which cannot be made of steel are a good candidate for GRP construction.

1.3.1 GRP Minesweeper Construction

Currently, minesweeper hulls in the 150 ft range are being constructed by the British, Italians, Swedish, and a Tripartite (Dutch-Belgian-French) consortium. A somewhat smaller hull has recently been announced by the Australians. The US Navy is evaluating several proposals for a coastal minesweeper, including two from U.S. shipbuilders incorporating European technology. The U.S. Navy has of course built many smaller GRP craft of its own, up to the 70 foot range. The European GRP ship designs are

generally an extension of the pleasure boat and US Navy GRP technology. They have added a large amount of their own developement and testing, including prototype ships, and the result has been improved analysis capabilities, production techniques, materials technology, and quality control.

The British ships are fabricated of isophthalic polyester resin and 24 oz/sq yd woven roving, with transverse hat-section frames bonded and then bolted to the hull to resist explosive loading. The complex framing system results in a high manhour fabrication, and the full structural strength characteristics of the material are not utilized due to buckling stiffness and secondary bonding strength limitations. The Tripartite minesweeper design is similar, except that two longitudinal girders in the machinery compartment reduce the span of the transverse bottom frames. Also, the stiffener faying flange connections to the hull are reinforced by GRP pins bonded into holes drilled through the flanges into the hull. Originally, a longitudinally framed hull using a rotating mold to allow downhand laminating of the stiffeners was proposed, but this approach was not selected for production. GRP sandwich panels are utilized in the Tripartite superstructure.

The Italian minesweeper class currently under construction departs from the previously mentioned designs in three major respects. First, it is a monocoque design without framing between bulkheads, allowing a semi-automated production method. Second, it utilizes 44 oz/sq yd woven roving (compared to 24 oz in other countries), which is impregnated and laid down mechanically, but rolled out by hand. They are reported to be working on methods for mechanical compaction and rolling out. Third, the resin used is a "toughened" isophthalic polyester which incorporates synthetic rubber in its formulation to improve resistance to cracking.

The Swedish Navy has developed the design of a minesweeper fabricated from a glass reinforced epoxy resin sandwich construction using a closed cell polyvinyl chloride (PVC) foam as a core. The lack of framing is a construction advantage as in the Italian hull, and the Swedes claim that the resistance to explosive (UNDEX) loading is better than solid framed hulls. British experience with foam cored sandwich construction showed problems with skin delamination, however, and due to the difficulty of inspection for failure areas, this construction has not gained favor with other navies for use below the waterline. It is, however, being used extensively for bulkheads, superstructures, and other areas not prone to catastrophic failure. More information on these and other contemporary applications of GRP to shipbuilding can be found in references 1-3 & 1-4.

REFERENCES - SECTION 1

NUMBER	TITLE
1-1	"Feasibility of Filament Winding Large Ship Hulls", J. L. McLarty, McClean-Anderson Laboratories, Menemone Falls, Wisconsin, Report No. J-2016 (Contract #00173-80-C-MT12) Dec. 1981.
1-2	"Proposal for Filament Winding of a Ship's Hull", LMSC-D086047, Lockheed Missiles & Space Co., Ocean Systems, 23 August 1982 (RFP N00014-82-12-BC62).
1-3	"The Challenge of an Innovative Contemporary Minesweeper", H. H. Vanderveldt & J. E. Gagorik, Dept of the Navy, Naval Sea Systems Command, Washington, D. C. 20362.
1-4	"Foreign Naval Developments in the Use of Glass Reinforced Plastics for Structural Applications", C.M. Hollyfield, W.R. Graner, M.J. Hammell. ARTECH Corporation, for Naval Intelligence Support Center, DTNSRDC/SME-80/37, AD-B050362.

SECTION 2
STRUCTURES

This section describes the structural evaluation and analysis which was performed in order to identify the general scantlings of a 150 ft filament wound minesweeper hull, and then to scale them down to the size of the 30 ft model. The loadings on a minesweeper hull include static heads of water, hull bending due to the action of waves, dynamic or assumed quasi-static UNDEX (UNDerwater EXplosion) loads, and static internal heads of water due to flooding. It is not possible to scale all of these loads down to model scale at the same time, since they are functions of different powers of the scale ratio. It was therefore undertaken, with the approval of the Navy, to apply the full scale loads to the conceptual design of a 150 ft minesweeper, to develop the full scale stress analysis and resultant structural scantlings, and then to scale the selected scantlings down to the model size of the 30 ft hull winding. An additional advantage of this procedure was the resultant determination of preliminary values for the full scale hull, since this lent some insight to the prospective problems which would have to be solved in developing a full scale filament wound minesweeper structure.

2.1 STRUCTURAL LOADS DEFINITION

This section will review the loads assigned at the beginning of the contract, the experience gained in previous GRP minesweeper structural designs, and the resultant approach to application of the design loads to the filament wound hull structural concept for both ship and model.

2.1.1 Assigned Loads

The structural loads assigned for the contract are listed in Table 2-1, with the hull bending moment and shear diagrams shown in Figure 2-1. Primary tensile, compressive, and shear stresses in the hull result from the application of the defined bending moment and shear envelopes, which approximate the loads due to hull bending on a wave. The secondary stress loads correspond to those caused by the hydrostatic head of a passing wave, the added hydrostatic head due to immersion caused by heeling, and the quasi-static pressure due to wave slap. Secondary stresses in the main deck simulate those from the head of water due to a solid wave on deck. The bulkhead loads simulate the head of water experienced when a damaged compartment is flooded and the spread of flooding is resisted by the bulkhead. The UNDEX quasi-static pressure simulates the dynamic loading due to a pressure wave from an underwater mine explosion, and is based on previous experience with the resistance of framed metal structures to these dynamic pressure loadings. The assigned factors of safety reflect the current level of knowledge with regard to the strength of GRP structures, along with available data on fatigue strength limits of fiberglass laminates in the marine atmosphere.

2.1.2 Current GRP Ship Structures Experience

The assigned loads were reviewed for comparison to those used in current and past GRP designs, and to identify the ones which were most significant to the design of a full scale filament wound hull. Review of the extensive work done by the British Ministry of Defence (MOD), and in particular the Naval Construction Research Establishment (NCRE) at Dunfermline Scotland, is most informative as to the principal design and fabrication problems in the design and construction of the prototype minehunter Wilton and the later MCMV class ships. Extensive information on these

Table 2-1

DESIGN LOADS FOR 140 FT FILAMENT WOUND GRP SHIP HULL

Load	Value
A. Primary Hull and Main Deck Stress	- Bending Moment and Shear as shown in Fig. 1
B. Secondary Hull Shell Plating Stresses	- The largest of the following hydrostatic loads: 1. Full load draft + 0.55 L 2. Head due to 35 deg heel at full load draft 3. 500 psf
C. Secondary Main Deck Stresses	- 4 ft hydrostatic head
D. Hull Plating and Framing	- UNDEX quasi-static pressure of 29.3 psi
E. Bulkhead Stresses	- Hydrostatic head initiating 4 ft below the weather deck
F. Factors of Safety	- A factor of 4 shall be used on the ultimate tensile, compressive, or shear strength, whichever is applicable

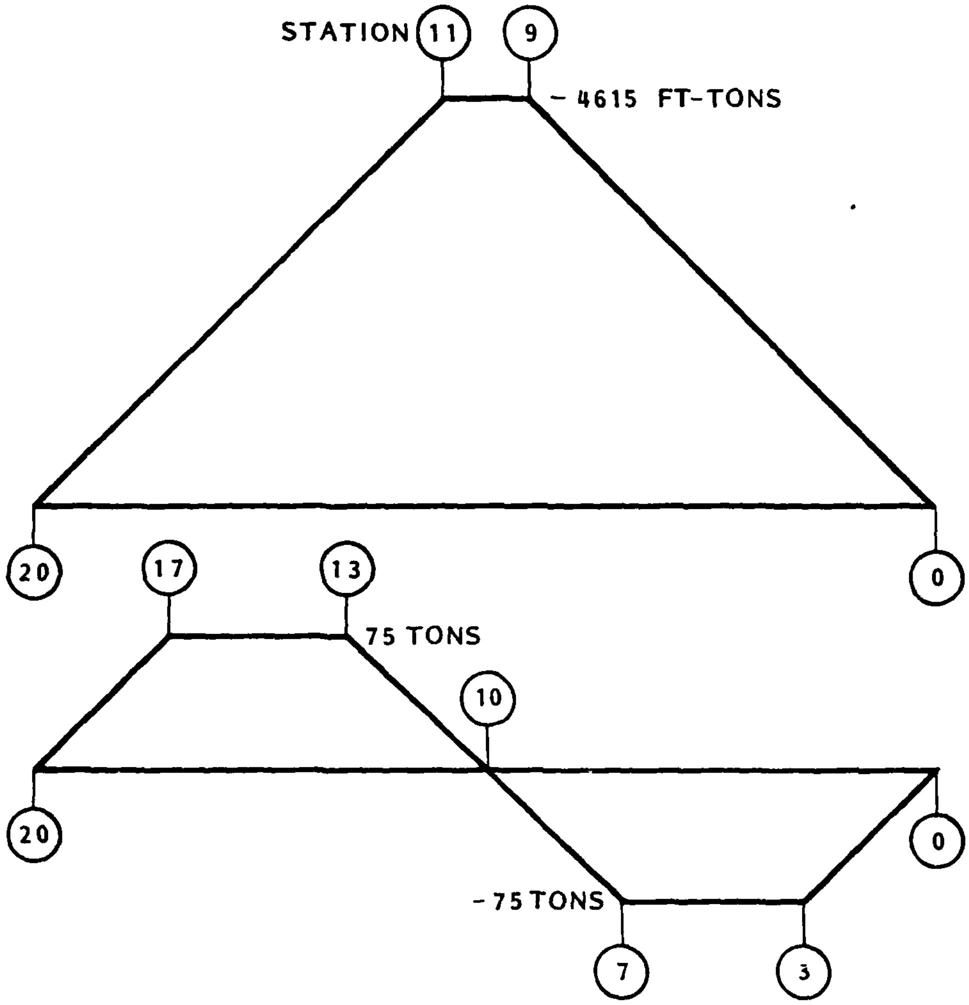

Fig. 2-1 Hull Bending Moment and Shear Loads

programs is contained in References 2-1 through 2-9, 2-11, and 2-20.

Traditionally, mine warfare ships have been of wood or wood composite constuction, and the scantlings have been developed based on the hull bending and local hydrostatic loads. UNDEX pressure loading was handled by means of testing of full scale models or prototypes, since the analytical tools were not available for direct treatment of dynamic pressure loading and the resulting structural response. In general, the wood designs required only minimal modifications, mostly in shear connections and foundation details, to make them satisfactory in resisting damage from mine explosions. This situation was principally the result of the very high stiffness to weight ratio of the wood material, along with the good shear characteristics of the bronze bolt and screw fastener details developed over many years of wood ship construction.

When the first GRP minesweeper sections were developed by the US Navy and British MOD, however, testing resulted in many shear and delamination failures under UNDEX loading. These were primarily the result of the low modulus of the GRP and resulting high deflections under load, the poor shear characteristics of the many secondary bonds, and the low interlaminar shear strength of the GRP laminate itself. In the British HMS Wilton and MCMV ships this led to the use of closely spaced transverse frames with mechanical fasteners at narrow intervals in the faying flanges to resist delamination under explosive load.

An additional problem not experienced by the wood ships was that the low GRP modulus made the hull plating subject to buckling failure long before the hull bending material reached its ultimate compressive stress, or even its working stress. In the case of the British ships, this problem caused the plating to be

designed for a working stress level of only about 3 to 4 ksi, even though the laminate had an ultimate limit of over 30 ksi, which would translate into a working stress of 7 to 8 ksi with a safety factor of 4 to allow for fatigue and other limitations.

In the British HMS Wilton and MCMV ships this led to the use of closely spaced transverse frames with mechanical fasteners at narrow intervals in the faying flanges to resist delamination under explosive load. The Tripartite vessels are able to use the longitudinal girders to help with the buckling problem, but also incorporate fasteners in the form of GRP pins to aid in resisting flange shear stresses.

The Italian hull avoids the shear stress problems by not using intermediate frames between bulkheads, and this results in a much thicker hull which is also better able to resist panel buckling under compressive hull bending loads. The penalty is in the weight of the thicker hull, but this is partially offset by elimination of the many framing joints and attachment flanges. The Italians have also reported significant bending stesses due to hull whipping under UNDEX loading, because of the low hull stiffness, and of course the thicker hull plating helps in resisting these loads, whereas the transverse framing material in other designs is not effective in this direction.

Further work in loads definition will be required before it is clear whether the critical loads for a GRP minesweeper with a monocoque hull would be the direct panel bending due to UNDEX pressure, the compressive buckling stress due to hull whipping caused by UNDEX loads, or simply the buckling limits imposed by static hull bending in conjunction with hydrostatic pressure on the panels. In this connection, it should be noted that current British practice is to calculate small ship hull bending for a wave height of L/9, which is somewhat more severe (24%) than the

US Navy criterion of 1.1 times the square root of L. The basis for this higher load is experience with steel trawlers and other small ships, and non-linearity problems associated with the use of wave loading techniques developed for much larger ships.

2.2 MATERIAL ALLOWABLES & WORKING STRESSES

Before calculating the stress levels and required scantlings resulting from the assigned loads, it was necessary to make some assumptions about the material properties that would result from filament winding a ship hull out of FRP. For purposes of the stress analysis, it was assumed that the hull winding would be produced from E Glass roving and polyester resin conforming to Navy specifications. Other applicable resins and reinforcements are also evaluated and discussed in Section 3 (Materials), but for purposes of the stress analysis, the polyester/glass assumption was adequate.

2.2.1 General GRP Data

A great deal of information has been developed with regard to the physical properties and analysis of composites, but the greater part of the analysis work has been done in the aerospace industry where the materials of interest are primarily high temperature cure epoxy resins and carbon fiber, Kevlar, boron, or other high strength / high cost reinforcements. In the marine industry, including the Navy, a large amount of fabrication and testing has been done using glass / polyester laminates, but due to cost, only a small amount of detailed analytical work comparable to that used in aerospace has been accomplished. Additionally, in the filament winding industry, most of the hard data available on material characteristics is again for those materials used in high strength / high cost applications, and very little good materials data is available for the type of polyester / glass

filament winding structure contemplated for a ship hull, at least in the form and detail needed for application of state-of-the-art machine analysis techniques.

2.2.2 Minesweeper GRP Materials Analysis

Some of the best work done to date on this subject of material characteristics versus glass reinforcement orientation and percentage composition was done in conjuction with the British MOD efforts mentioned previously.(2-1) This work reviewed the theories available for evaluation of material properties, and provided the information necessary to compute values of the tensile and shear modulii (E and G), and the Poisson ratio (ν), for laminates of various resin percentages and fiber orientations. This approach was followed in deriving the materials characteristics as discussed in the following paragraphs. Further discussion of these methods is also provided in a DTNSRDC report by Milton Critchfield.(2-10)

2.2.3 Reinforcement Glass Ratio

Because the percentage of glass that will be achieved by filament winding a hull shape is not known with certainty at this time, stress calculations were made parametrically for assumed glass content (by weight) of 50, 60, and 70 percent. Hand layup roving hulls generally achieve about 50%, which is is thus regarded as a lower limit and included for comparison. A 70% glass content is often achieved in the filament winding of cylindrical shapes, and is therefore included as a goal for the winding of the model. The intermediate value of 60% is probably a reasonably conservative estimate for use in examining the feasibility of filament winding a ships hull, and was thus used for purposes of selecting scantlings for the ship and model. Material samples produced early in the next phase, before the model is wound, could be used to

verify this assumption and revise the hull thickness before winding.

2.2.4 Calculated Material Properties

Using the approach and procedures referenced above, the material characteristics shown in Table 2-2 were developed. It will be seen from these results that the glass percentage achieved will have a significant effect on the material properties for design, increasing the tensile and shear modulii by over 50% as the glass content is raised from 50 to 70%. The Poisson ratio is not as significantly affected, although it appears to be a minimum at about 60% glass. As previously mentioned, the higher glass content is also known to result in greater resistance to support of combustion, and is very desirable in a ship structure for that reason, possibly affecting the need for fire retardents in the resin.

2.2.5 Balanced versus Unbalanced Laminates

Smith's analysis also allows a comparison of material properties for balanced and unbalanced laminates as a function of fiber direction, and a comparison is shown in Table 2-3 between the properties of the balanced laminate and a unidirectional laminate. As this demonstrates, orienting the fibers in the direction of the principal stresses can result in almost doubling the tensile modulus. This is significant to the design of a filament wound hull, since the fabrication method would allow orienting the majority of the fibers in the direction of the bending or other principal stress, resulting in a higher structural efficiency than is achieved in a balanced laminate, which in effect tries to emulate an orthotropic material.

In order to take advantage of this possibility, it would be

Table 2-2

MATERIAL PROPERTIES VERSUS GLASS CONTENT - BALANCED LAMINATES

Percent Glass	50	60	70
Young's Modulus - E, psi	2.3×10^6	2.8×10^6	3.5×10^6
Shear Modulus - G, psi	4.7×10^5	5.7×10^5	7.3×10^5
Poisson Ratio - ν, psi	0.12	0.11	0.12

Table 2-3

COMPARISON OF BALANCED AND UNIDIRECTIONAL LAMINATE PROPERTIES

Quantity	Balanced Laminate	Unidirectional Laminate
Young's Modulus - E_{11}, psi	2.3×10^6	3.6×10^6
Young's Modulus - E_{22}, psi	2.3×10^6	1.0×10^6
Shear Modulus - G_{12}, psi	4.7×10^5	4.7×10^5
Shear Modulus - G_{21}, psi	4.7×10^5	-
Poisson Ratio - $_{12}$	0.12	0.29
Poisson Ratio - $_{21}$	0.12	0.08

Note: Both laminates 50% glass (weight)

necessary to accomplish and verify a detailed finite element stress analysis of the entire hull, using known and verified loading values. The work already accomplished by the British with regard to hull stress provides a good begining for this investigation, however, and indicates the direction in which such an investigation should proceed. Since this has not been accomplished for a ship such as a minesweeper, and is well beyond the scope of this investigation, the assumption of a balanced laminate was used for analizing the stress and selecting scantlings for the model.

2.2.6 Ultimate & Working Stress Levels

The elastic properties discussed above are necessary to the calculation of deflections and stresses, but do not address the question of what the ultimate fracture stress or allowable working stress levels in the materials would be. Data for hand layup GRP is available from a variety of sources, and generally covers cloth laminates, mat laminates, and combination mat and woven roving laminates. The characteristics are strongly dependent on glass content, laminating methods, and quality control.

2.2.6.1 Woven Roving Laminate Strength Data. Work done by the Navy on this subject dates back over 15 years, with some of the first data published in a paper on GRP minesweepers in 1965.[2-13] A significant amount of additional work was done on a full scale midships section of a minesweeper which was designed[2-14], fabricated[2-15], and tested under UNDEX loading in 1969-70. The British MOD accomplished a large amount of testing for the HMS Wilton in 70-72[2-7], and further testing for the current MCMV class vessels. Several laminates of Kevlar, GRP, polyester, and vinyl ester were tested and report by NSRDC in 1981[2-16]. All of the above were basically woven roving hand layup laminates, and the reported results of their testing is summarized in Table 2-4.

Table 2-4 GRP ULTIMATE STRESS DATA - VARIOUS SOURCES

Source	Lam. Type	% Glass	S.G.	Flex ULT(a)	F_{1T} Tensile ULT (11)	F_{1C} Comp ULT (11)	F_{2T} Transverse Tens ULT (1)	F_{2C} Transverse Comp. ULT (1)	F_6 Interlam. Shear	F_{22} Transverse Shear
Spaulding - Della Roca (17)	W.R.	50-57	1.65	31-54	35-40	16-35	28/40(b)	31/35	1.6	14-16
Langford-Angerer (18) (Design Values)	W.R.	56	-	39.6	51.2	35.3	-	-	1.7	-
Peterson-Owens Corning (19) (Test Data)	W.R.	48-56	-	36-45	33-41	21-30			0.8-1.5	12-18
British MOD-Wilton (11)	W.R.	50	1.7	30	33-35	27	(24/40)	(27/30)	2.0	16
DTNSRDC-Goldfarb (20)	Polyester/WR	51.6	1.8	44.3	42.5	-	-	-	4.2	-
	Vinyl Ester/WR	53.4	1.75	47.6	42.9	-	-	-	4.6	-
Vickers Slingsby	Unidirect	70	-	-	130	70	-	-	7.2	5.8
McClean Anderson - Vinyl Ester/E-glass	F.W.	75	-	-	150	85	5.2	5.2	o	o
NEMA Report (21)	F.W.	70	-	-	85	-	10	-	-	-

(a) All values in Ksi (Kips/inch^2)

(b) Ratio of transverse to parallel

(-) Indicates no data available

It will be seen that the woven roving laminates all have glass percentages of 50 to 56, and tensile and flexural strengths of about 33 to 50 and 30 to 48 ksi, respectively. Compressive strengths are 10 to 20% lower, and transverse shear strengths in the range of 13 to 16 ksi. Interlaminar shear strengths are in the range of 1 to 4 ksi, and show more variation, probably as a result of manufacturing methods and controls.

2.2.6.2 Filament Wound Laminate Data. For comparison, data on filament wound roving/polyester and vinyl ester laminates from several sources is also included. The filament wound laminates have higher glass percentages, from 70 to 75%, and the resultant tensile and compressive ultimates are about double the values for the woven roving laminates. The reasons for this increased strength include more effective orientation of the fibers with regard to the direction of principal stress, lower resin content due to the clamping or compressive effect of the cylindrical winding, and the absence of bending of the fibers as in woven fabrics.

2.2.6.3 Selection of Strength Values for Model Design. The selection of best estimate values for use in designing a model filament wound hull is therefore a matter of judgement in evaluating the probable retention of these factors in a large, non-circular, tapering hull shape. As will be discussed in Section 2.4, the selection of ship scantlings is primarily a matter of varying the number of repetitions of the basic winding patterns, and can therefore be made or modified after testing sample sections of a test winding made on the 30 foot model mandrel before winding the final model hull. For purposes of stress analysis and preliminary selection of scantlings, however, it may be assumed that the achieved glass percentage will be between the 50% hand layup value and the 70% achieved in cylindrical filament windings. If the value of 60% is therefore used for design purposes,

the ultimate strength values for design will be approximately intermediate between the woven roving and filament wound values in Table 2-4. Additionally, the orientation of the fibers in the selected laminate, when compared to the direction of principal stress, must be taken into account. This selection will be discussed in Section 2.4.

2.3 HULL STRESS CALCULATIONS

As a result of the foregoing experience, the procedure adopted for this investigation was to check the hull panels between bulkheads for stresses due to: (a) UNDEX quasi-static pressure loading; (b) compressive loading due to hull bending; and (c) panel buckling limits, assuming no stiffening between bulkheads. These calculations were done in a parametric manner, since the thickness and structural allowables of the GRP laminate were not defined at the time of the calculations. The following sections discuss each of these loads, and the resultant stress levels versus parametric material characteristics and hull scantlings. The selection of material characterisrics was discussed in Section 2.2, and the resultant ship and model scantlings will be discussed in Sections 2.4 and 2.5, respectively.

2.3.1 Hull Bending in Waves

Traditionally, the major criteria for selection of shell scantlings for ships has been the hull tensile and compresive stress resulting from the static bending of the ship on a wave of some assumed length, such as 1.1 times the square root of the ship length. Sometimes, as in the case of very small ships, local loadings on the shell plating will result in scantling requirements greater than those imposed by the hull bending, and these local loadings often predominate near the end of the ship where the bending loads are reduced. In the case of a minesweeper,

UNDEX loads may predominate.

2.3.1.1 Initial Bending Calculations. As a first step in evaluating the structural requirements of a filament wound minesweeper hull, the assigned bending moment distribution was used to calculate the deck and keel stress using the MCM-1 lines, provided for use in studying the filament winding patterns. It was assumed that the main deck is not effective in bending, due to its location near the neutral axis. To correct for the difference in ship size, the lines were scaled down to the 150 length (140 ft LBP) of the concept MSH for which preliminary lines were provided.

Table 2-5 shows the result of this calculation, for shell thicknesses of 1, 2, and 3 inches. The first thing noted from this analysis is that the stress levels along the length of the hull are fairly uniform from stations 6 to 16, with the exception of station 14, where the stress level is about doubled by the assumption that the deck is removed in way of the uptake openings. Assuming for the moment that this bending material is replaced by local reinforcement and utilization of the deck plating between the uptakes (which was not assumed in the calculation), the major conclusion to be drawn is that the hull thickness could be essentially constant throughout the midships half-length. This means that for purposes of designing the filament winding, the major portion of the hull can be considered a non-circular cylinder of constant thickness. (Of course, the topsides thickness could be reduced by ommitting some of the axial layers, but the basically transverse layers will have to extend all the way around the hull.)

The second point of significance is that for hull thicknesses of 1 to 2 inches, as used in the British and Tripartite minesweepers, the stress level was somewhat higher than that calculated

Table 2-5

PRIMARY STRESS DUE TO HULL BENDING - MCM-1 LINES*

*Note: Lines scaled to 140 ft LBP

Shell/Deck Thickness	1 in.	2 in.	3 in.
Station	Stress (psi)		
2	1,095	548	365
4	1,640	820	547
6	1,870	935	624
8	2,141	1,070	714
10	2,262	1,131	754
12	2,487	1,244	829
14	4,402	2,201	1,467
16	1,536	768	512
18	1,125	562	375

Table 2-6

MSH VERSUS SCALED MCM-1 DIMENSIONS

Characteristic	MCM-1	MCM x 0.681(1)	MSH(2)
LBP	205.5	140.0	140.0
LOA	217.0	147.8	152.0
Beam, DWL, Max.	38.6	26.3	27.3
Beam, Extreme	38.9	26.5	30.5
Draft, DWL	9.5	6.5	8.0
Depth, 01 Dk	24.0	16.4	21.5
Depth, Main Dk, Aft	17.5	11.9	24.5

(1) LBP of MCM / LBP of MSH

(2) Concept MSH - NAVSEA 4/14/82

for those designs. It was noted that the MCM hull lines, when scaled down to a length equal to the proposed MSH, had resulted in a hull beam and depth substantially less than that of the European designs or the concept lines included with the bending moment curves in the RFQ for this study. This can be seen in Table 2-6. It was therefore decided to recalculate the hull bending stress using the concept MSH lines, to see if the results appeared to be more consistant with the British results. This had the additional advantage of allowing the use of the bulkhead locations directly from the concept MSH arrangement, instead of trying to interpolate between the two designs.

2.3.1.2 Parametric Bending Moment Stress Analysis. Figures 2-2 through 2-9 show the results of the MSH hull bending stress calculawion for assumed hull and deck thicknesses from 2 to 6 inches. These were included because the hull is expected to be thicker than the 1 to 2 inches of the European designs if closely spaced framing is to be avoided, but not substantially thicker than the 4 to 5 inches reported for the monocoque Italian design. The calculations are summarized in Table 2-7. It should be noted that as in the previous calculation, the main deck was not considered to be effective in bending. The use of the same thickness for the hull and 01 deck results in an unbalanced bending stress distribution at the upper and lower fibers of the hull beam, but a reduction of 1 inch in the thickness of the weather deck results in a much more balanced and thus lighter design. These scantlings will of course also depend on local secondary loads and buckling allowables, to be discussed in the following sections.

The major conclusions to be gained from these preliminary calculations were that the stress per unit thickness due to hull bending would be about the same as that resulting from the design loads and scantlings of the European designs, but that buckling

HULL STRESS DUE TO BENDING MOMENT - FWSH

MOMENT OF INERTIA - SHELL AND DECK   t(SHELL)= 3.0   t(DECK)=3.0

STATION 10 - MOLDED OFFSETS AND SECTION MODULUS

HEIGHT (FT)	BREADTH/2 (FT)	AREA (FT-IN)	y (FT)	Ay (FT^2-IN)	Ay^2 (FT^3-IN)	Io (FT^3-IN)	SINA	COSA
0.40	0.00	0	0.00	0	0	0	0	0
0.80	6.00	18.04	-9.40	-169.58	1594.0	4.0	0.9978	0.0665
1.00	8.00	6.03	-9.10	-54.87	499.3	0.6	0.9950	0.0995
1.45	10.00	6.15	-8.78	-53.97	473.6	1.6	0.9756	0.2195
2.40	12.00	6.64	-8.08	-53.64	433.1	6.3	0.9033	0.4291
4.00	13.70	7.00	-6.80	-47.62	323.8	18.2	0.7282	0.6854
6.00	14.55	6.52	-5.00	-32.60	163.0	26.1	0.3911	0.9203
8.00	14.92	6.10	-3.00	-18.31	54.9	24.4	0.1819	0.9833
10.00	15.08	6.02	-1.00	-6.02	6.0	24.1	0.0797	0.9968
14.00	15.00	12.00	2.00	24.00	48.0	192.0	-0.0200	0.9998
16.00	14.92	6.00	5.00	30.02	150.1	24.0	-0.0400	0.9992
22.00	14.25	18.11	9.00	163.01	1467.1	652.0	-0.1110	0.9938
22.36	0.00	42.76	12.18	520.78	6342.1	8.1	-0.9997	0.0250
SUMS (HALF-SHIP):		141.39		301.22	11555.1	981.6		
					981.6			

MOMENT OF INERTIA ABOUT WL-10= 12536.6

$$\text{NEUTRAL AXIS FROM WL 10} = \frac{301.2}{141.4} = 2.13$$

NEUTRAL AXIS ABOVE BASELINE = 12.13

MOMENT OF INERTIA ABOUT NEUTRAL AXIS = 11895 x 2 SIDES=23790

BASELINE TO NEUTRAL AXIS, FT= 12.13   KEEL SECTION MODULUS, FT^2-IN=1961

DECK @CL TO NEUTRAL AXIS, FT= 10.23   DECK SECTION MODULUS, FT^2-IN=2326

BENDING MOMENT = 4615 FT-TONS

MAXIMUM STRESS AT KEEL, PSI = 439.3

MAXIMUM STRESS AT DECK, PSI = 370.3

****
HULL STRESS DUE TO BENDING MOMENT - FWSH
****
****
MOMENT OF INERTIA - SHELL AND DECK   t(SHELL)= 3.0   t(DECK)=2.0
****
STATION 10 - MOLDED OFFSETS AND SECTION MODULUS

HEIGHT (FT)	BREADTH/2 (FT)	AREA (FT-IN)	y (FT)	Ay (FT^2-IN)	Ay^2 (FT^3-IN)	Io (FT^3-IN)	SINA	COSA
0.40	0.00	0	0.00	0	0	0	0	0
0.80	6.00	18.04	-9.40	-169.58	1594.0	4.0	0.9978	0.0665
1.00	8.00	6.03	-9.10	-54.87	499.3	0.6	0.9950	0.0995
1.45	10.00	6.15	-8.78	-53.97	473.6	1.6	0.9756	0.2195
2.40	12.00	6.64	-8.08	-53.64	433.1	6.3	0.9033	0.4291
4.00	13.70	7.00	-6.80	-47.62	323.8	18.2	0.7282	0.6854
6.00	14.55	6.52	-5.00	-32.60	163.0	26.1	0.3911	0.9203
8.00	14.92	6.10	-3.00	-18.31	54.9	24.4	0.1819	0.9833
10.00	15.08	6.02	-1.00	-6.02	6.0	24.1	0.0797	0.9968
14.00	15.00	12.00	2.00	24.00	48.0	192.0	-0.0200	0.9998
16.00	14.92	6.00	5.00	30.02	150.1	24.0	-0.0400	0.9992
22.00	14.25	18.11	9.00	163.01	1467.1	652.0	-0.1110	0.9938
22.36	0.00	28.51	12.18	347.19	4228.1	7.6	-1.4995	0.0375
SUMS (HALF-SHIP):		127.13		127.62	9441.0	981.1		
					981.1			

MOMENT OF INERTIA ABOUT WL-10= 10422.1

NEUTRAL AXIS FROM WL 10 = 127.6 / 127.1 = 1.00

NEUTRAL AXIS ABOVE BASELINE = 11.00

MOMENT OF INERTIA ABOUT NEUTRAL AXIS = 10294 × 2 SIDES=20588
****
BASELINE TO NEUTRAL AXIS, FT= 11.00   KEEL SECTION MODULUS, FT^2-IN=1871

DECK BCL TO NEUTRAL AXIS, FT= 11.35   DECK SECTION MODULUS, FT^2-IN=1814
****
BENDING MOMENT =   4615 FT-TONS

MAXIMUM STRESS AT KEEL, PSI = 460.4

MAXIMUM STRESS AT DECK, PSI = 475.0
****

HULL STRESS DUE TO BENDING MOMENT - FWSH

MOMENT OF INERTIA - SHELL AND DECK   t(SHELL)= 4.0   t(DECK)=4.0

STATION 10 - MOLDED OFFSETS AND SECTION MODULUS

HEIGHT (FT)	BREADTH/2 (FT)	AREA (FT-IN)	y (FT)	Ay (FT^2-IN)	Ay^2 (FT^3-IN)	Io (FT^3-IN)	SINA	COSA
0.40	0.00	0	0.00	0	0	0	0	0
0.80	6.00	24.05	-9.40	-226.10	2125.3	6.5	0.9978	0.0665
1.00	8.00	8.04	-9.10	-73.16	665.8	1.2	0.9950	0.0995
1.45	10.00	8.20	-8.78	-71.96	631.4	2.5	0.9756	0.2195
2.40	12.00	8.86	-8.08	-71.52	577.5	8.8	0.9033	0.4291
4.00	13.70	9.34	-6.80	-63.50	431.8	24.5	0.7282	0.6854
6.00	14.55	8.69	-5.00	-43.46	217.3	34.9	0.3911	0.9203
8.00	14.92	8.14	-3.00	-24.41	73.2	32.6	0.1819	0.9833
10.00	15.08	8.03	-1.00	-8.03	8.0	32.1	0.0797	0.9968
14.00	15.00	16.00	2.00	32.01	64.0	256.1	-0.0200	0.9998
16.00	14.92	8.01	5.00	40.03	200.2	32.0	-0.0400	0.9992
22.00	14.25	24.15	9.00	217.34	1956.1	869.4	-0.1110	0.9938
22.36	0.00	57.02	12.18	694.37	8456.1	13.6	-0.9997	0.0250
SUMS (HALF-SHIP):		188.52		401.62	15406.8	1314.1		
					1314.1			

MOMENT OF INERTIA ABOUT WL-10= 16720.9

$$\text{NEUTRAL AXIS FROM WL 10} = \frac{401.6}{188.5} = 2.13$$

NEUTRAL AXIS ABOVE BASELINE = 12.13

MOMENT OF INERTIA ABOUT NEUTRAL AXIS = 15865 x 2 SIDES=31731

BASELINE TO NEUTRAL AXIS, FT= 12.13   KEEL SECTION MODULUS, FT^2-IN=2616

DECK @CL TO NEUTRAL AXIS, FT= 10.23   DECK SECTION MODULUS, FT^2-IN=3103

BENDING MOMENT = 4615 FT-TONS

MAXIMUM STRESS AT KEEL, PSI = 329.3

MAXIMUM STRESS AT DECK, PSI = 277.6

HULL STRESS DUE TO BENDING MOMENT - FWSH

MOMENT OF INERTIA - SHELL AND DECK t(SHELL)= 4.0 t(DECK)=3.0

STATION 10 - MOLDED OFFSETS AND SECTION MODULUS

HEIGHT (FT)	BREADTH/2 (FT)	AREA (FT-IN)	y (FT)	Ay (FT^2-IN)	Ay^2 (FT^3-IN)	Io (FT^3-IN)	SINA	COSA
0.40	0.00	0	0.00	0	0	0	0	0
0.80	6.00	24.05	-9.40	-226.10	2125.3	6.5	0.9978	0.0665
1.00	8.00	8.04	-9.10	-73.16	665.8	1.2	0.9950	0.0995
1.45	10.00	8.20	-8.78	-71.96	631.4	2.5	0.9756	0.2195
2.40	12.00	8.86	-8.08	-71.52	577.5	8.8	0.9033	0.4291
4.00	13.70	9.34	-6.80	-63.50	431.8	24.5	0.7282	0.6854
6.00	14.55	8.69	-5.00	-43.46	217.3	34.9	0.3911	0.9203
8.00	14.92	8.14	-3.00	-24.41	73.2	32.6	0.1819	0.9833
10.00	15.08	8.03	-1.00	-8.03	8.0	32.1	0.0797	0.9968
14.00	15.00	16.00	2.00	32.01	64.0	256.1	-0.0200	0.9998
16.00	14.92	8.01	5.00	40.03	200.2	32.0	-0.0400	0.9992
22.00	14.25	24.15	9.00	217.34	1956.1	869.4	-0.1110	0.9938
22.36	0.00	42.76	12.18	520.78	6342.1	13.9	-1.3329	0.0333
SUMS (HALF-SHIP):		174.26		228.03	13292.7	1314.4		
					1314.4			

MOMENT OF INERTIA ABOUT WL-10= 14607.2

$$\text{NEUTRAL AXIS FROM WL 10} = \frac{228.0}{174.3} = 1.31$$

NEUTRAL AXIS ABOVE BASELINE = 11.31

MOMENT OF INERTIA ABOUT NEUTRAL AXIS = 14309 x 2 SIDES=28618

BASELINE TO NEUTRAL AXIS, FT= 11.31 KEEL SECTION MODULUS, FT^2-IN=2531

DECK @CL TO NEUTRAL AXIS, FT= 11.05 DECK SECTION MODULUS, FT^2-IN=2590

BENDING MOMENT = 4615 FT-TONS

MAXIMUM STRESS AT KEEL, PSI = 340.4

MAXIMUM STRESS AT DECK, PSI = 332.6

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******************************************************************************
HULL STRESS DUE TO BENDING MOMENT - FWSH
******************************************************************************
******************************************************************************
MOMENT OF INERTIA - SHELL AND DECK      t(SHELL)= 5.0        t(DECK)=5.0
******************************************************************************
STATION 10 - MOLDED OFFSETS AND SECTION MODULUS
```

HEIGHT (FT)	BREADTH/2 (FT)	AREA (FT-IN)	y (FT)	Ay (FT^2-IN)	Ay^2 (FT^3-IN)	Io (FT^3-IN)	SINA	COSA
0.40	0.00	0	0.00	0	0	0	0	0
0.80	6.00	30.07	-9.40	-282.63	2656.7	10.0	0.9978	0.0665
1.00	8.00	10.05	-9.10	-91.45	832.2	2.1	0.9950	0.0995
1.45	10.00	10.25	-8.78	-89.94	789.3	3.8	0.9756	0.2195
2.40	12.00	11.07	-8.08	-89.40	721.9	11.6	0.9033	0.4291
4.00	13.70	11.67	-6.80	-79.37	539.7	31.0	0.7282	0.6854
6.00	14.55	10.87	-5.00	-54.33	271.6	43.8	0.3911	0.9203
8.00	14.92	10.17	-3.00	-30.51	91.5	40.7	0.1819	0.9833
10.00	15.08	10.03	-1.00	-10.03	10.0	40.1	0.0797	0.9968
14.00	15.00	20.00	2.00	40.01	80.0	320.1	-0.0200	0.9998
16.00	14.92	10.01	5.00	50.04	250.2	40.0	-0.0400	0.9992
22.00	14.25	30.19	9.00	271.68	2445.1	1086.8	-0.1110	0.9938
22.36	0.00	71.27	12.18	867.96	10570.2	21.4	-0.9997	0.0250
SUMS (HALF-SHIP):		235.65		502.03	19258.5	1651.3		
					1651.3			

```
                    MOMENT OF INERTIA ABOUT WL-10=  20909.8

                                                502.0
                       NEUTRAL AXIS FROM WL 10 = ------- =  2.13
                                                235.6

                    NEUTRAL AXIS ABOVE BASELINE =  12.13

                     MOMENT OF INERTIA ABOUT NEUTRAL AXIS =  19840   x 2 SIDES=39681
******************************************************************************
BASELINE TO NEUTRAL AXIS, FT= 12.13      KEEL SECTION MODULUS, FT^2-IN=3271

DECK @CL TO NEUTRAL AXIS, FT= 10.23      DECK SECTION MODULUS, FT^2-IN=3880
******************************************************************************
   BENDING MOMENT =        4615 FT-TONS

MAXIMUM STRESS AT KEEL, PSI = 263.4

MAXIMUM STRESS AT DECK, PSI = 222.0
******************************************************************************
```

HULL STRESS DUE TO BENDING MOMENT - FWSH

MOMENT OF INERTIA - SHELL AND DECK   t(SHELL)= 5.0   t(DECK)=4.0

STATION 10 - MOLDED OFFSETS AND SECTION MODULUS

HEIGHT (FT)	BREADTH/2 (FT)	AREA (FT-IN)	y (FT)	Ay (FT^2-IN)	Ay^2 (FT^3-IN)	Io (FT^3-IN)	SINA	COSA
0.40	0.00	0	0.00	0	0	0	0	0
0.80	6.00	30.07	-9.40	-282.63	2656.7	10.0	0.9978	0.0665
1.00	8.00	10.05	-9.10	-91.45	832.2	2.1	0.9950	0.0995
1.45	10.00	10.25	-8.78	-89.94	789.3	3.8	0.9756	0.2195
2.40	12.00	11.07	-8.08	-89.40	721.9	11.6	0.9033	0.4291
4.00	13.70	11.67	-6.80	-79.37	539.7	31.0	0.7282	0.6854
6.00	14.55	10.87	-5.00	-54.33	271.6	43.8	0.3911	0.9203
8.00	14.92	10.17	-3.00	-30.51	91.5	40.7	0.1819	0.9833
10.00	15.08	10.03	-1.00	-10.03	10.0	40.1	0.0797	0.9968
14.00	15.00	20.00	2.00	40.01	80.0	320.1	-0.0200	0.9998
16.00	14.92	10.01	5.00	50.04	250.2	40.0	-0.0400	0.9992
22.00	14.25	30.19	9.00	271.68	2445.1	1086.8	-0.1110	0.9938
22.36	0.00	57.02	12.18	694.37	8456.1	22.7	-1.2496	0.0312
SUMS (HALF-SHIP):		221.39		328.43	17144.4	1652.6		
					1652.6			

MOMENT OF INERTIA ABOUT WL-10= 18797.1

$$\text{NEUTRAL AXIS FROM WL 10} = \frac{328.4}{221.4} = 1.48$$

NEUTRAL AXIS ABOVE BASELINE = 11.40

MOMENT OF INERTIA ABOUT NEUTRAL AXIS = 18310   x 2 SIDES=36620

BASELINE TO NEUTRAL AXIS, FT= 11.48   KEEL SECTION MODULUS, FT^2-IN=3189

DECK MOL TO NEUTRAL AXIS, FT= 10.87   DECK SECTION MODULUS, FT^2-IN=3368

BENDING MOMENT =   4615 FT-TONS

MAXIMUM STRESS AT KEEL, PSI = 270.1

MAXIMUM STRESS AT DECK, PSI = 255.8

HULL STRESS DUE TO BENDING MOMENT - FWSH

MOMENT OF INERTIA - SHELL AND DECK t(SHELL)= 6.0 t(DECK)=6.0

STATION 10 - MOLDED OFFSETS AND SECTION MODULUS

HEIGHT (FT)	BREADTH/2 (FT)	AREA (FT-IN)	y (FT)	Ay (FT^2-IN)	Ay^2 (FT^3-IN)	Io (FT^3-IN)	SINA	COSA
0.40	0.00	0	0.00	0	0	0	0	0
0.80	6.00	36.08	-9.40	-339.15	3188.0	14.8	0.9978	0.0665
1.00	8.00	12.06	-9.10	-109.74	998.7	3.5	0.9950	0.0995
1.45	10.00	12.30	-8.78	-107.93	947.1	5.4	0.9756	0.2195
2.40	12.00	13.28	-8.08	-107.28	866.3	14.7	0.9033	0.4291
4.00	13.70	14.01	-6.80	-95.25	647.7	37.7	0.7282	0.6854
6.00	14.55	13.04	-5.00	-65.19	326.0	52.7	0.3911	0.9203
8.00	14.92	12.20	-3.00	-36.61	109.8	48.9	0.1819	0.9833
10.00	15.08	12.04	-1.00	-12.04	12.0	48.2	0.0797	0.9968
14.00	15.00	24.00	2.00	48.01	96.0	384.1	-0.0200	0.9998
16.00	14.92	12.01	5.00	60.05	300.2	48.0	-0.0400	0.9992
22.00	14.25	36.22	9.00	326.01	2934.1	1304.2	-0.1110	0.9938
22.36	0.00	85.53	12.18	1041.56	12684.2	32.2	-0.9997	0.0250
SUMS (HALF-SHI.):		282.78		602.43	23110.2	1994.3		
					1994.3			

MOMENT OF INERTIA ABOUT WL-10= 25104.5

NEUTRAL AXIS FROM WL 10 = 602.4 / 282.8 = 2.13

NEUTRAL AXIS ABOVE BASELINE = 12.13

MOMENT OF INERTIA ABOUT NEUTRAL AXIS = 23821 x 2 SIDES=47642

BASELINE TO NEUTRAL AXIS, FT= 12.13 KEEL SECTION MODULUS, FT^2-IN=3927

DECK @CL TO NEUTRAL AXIS, FT= 10.23 DECK SECTION MODULUS, FT^2-IN=4659

BENDING MOMENT = 4615 FT-TONS

MAXIMUM STRESS AT KEEL, PSI = 219.3

MAXIMUM STRESS AT DECK, PSI = 184.9

HULL STRESS DUE TO BENDING MOMENT - FWSH

MOMENT OF INERTIA - SHELL AND DECK t(SHELL)= 6.0 t(DECK)=5.0

STATION 10 - MOLDED OFFSETS AND SECTION MODULUS

HEIGHT (FT)	BREADTH/2 (FT)	AREA (FT-IN)	y (FT)	Ay (FT^2-IN)	Ay^2 (FT^3-IN)	Io (FT^3-IN)	SINA	COSA
0.40	0.00	0	0.00	0	0	0	0	0
0.80	6.00	36.08	-9.40	-339.15	3188.0	14.8	0.9978	0.0665
1.00	8.00	12.06	-9.10	-109.74	998.7	3.5	0.9950	0.0995
1.45	10.00	12.30	-8.78	-107.93	947.1	5.4	0.9756	0.2195
2.40	12.00	13.28	-8.08	-107.28	866.3	14.7	0.9033	0.4291
4.00	13.70	14.01	-6.80	-95.25	647.7	37.7	0.7282	0.6854
6.00	14.55	13.04	-5.00	-65.19	326.0	52.7	0.3911	0.9203
8.00	14.92	12.20	-3.00	-36.61	109.8	48.9	0.1819	0.9833
10.00	15.08	12.04	-1.00	-12.04	12.0	48.2	0.0797	0.9968
14.00	15.00	24.00	2.00	48.01	96.0	384.1	-0.0200	0.9998
16.00	14.92	12.01	5.00	60.05	300.2	48.0	-0.0400	0.9992
22.00	14.25	36.22	9.00	326.01	2934.1	1304.2	-0.1110	0.9938
22.36	0.00	71.27	12.18	867.96	10570.2	34.7	-1.1996	0.0300
SUMS (HALF-SHIP):		268.52		428.84	20996.1	1996.8		
					1996.8			

MOMENT OF INERTIA ABOUT WL-10= 22992.9

$$\text{NEUTRAL AXIS FROM WL 10} = \frac{428.8}{268.5} = 1.60$$

NEUTRAL AXIS ABOVE BASELINE = 11.60

MOMENT OF INERTIA ABOUT NEUTRAL AXIS = 22308 x 2 SIDES=44616

BASELINE TO NEUTRAL AXIS, FT= 11.60 KEEL SECTION MODULUS, FT^2-IN=3847

DECK @CL TO NEUTRAL AXIS, FT= 10.76 DECK SECTION MODULUS, FT^2-IN=4147

BENDING MOMENT = 4615 FT-TONS

MAXIMUM STRESS AT KEEL, PSI = 223.9

MAXIMUM STRESS AT DECK, PSI = 207.7

Table 2-7

SUMMARY - HULL BENDING STRESSES

Thickness (in.)		Stress Level (psi)	
Shell	Deck	Keel	Deck
3.0	3.0	439	370
3.0	2.0	460	475
4.0	4.0	329	278
4.0	3.0	340	333
5.0	5.0	263	222
5.0	4.0	270	256
6.0	6.0	219	185
6.0	5.0	224	208

stress levels would have to be analized and compared to the bending stress to see if hull bending or UNDEX panel bending would control the required scantlings.

2.3.2 Shell & Deck Buckling Stresses

For purposes of analizing the deflection and stress in the bottom panels under explosive loading, it was assumed that the panels extended from bulkhead to bulkhead, and from the centerline to the turn of the bilge, without any intermediate stiffeners. These assumptions are supported by the results of small scale panel buckling tests performed during the design of the British MCMV (2-11).

2.3.2.1 Analytical Approach. As in the case of the hull bending stress discussed in the previous section, the calculation was repeated for 50, 60, and 70% glass properties, and for hull thicknesses of 3, 4, 5, and 6 inches. The first calculation made was for column buckling of a simply supported strip of shell 12 inches wide, and extending from bulkhead to bulkhead. This is a conservative calculation that served to bound the problem. The next calculations were for the critical stress in a panel of bottom plating as defined above, and for a deck panel the full width of the ship except in way of the uptake openings, where the width was the distance between hatches across the centerline of the ship. These two calcultions were made for two different assumptions: simple support at the edges and clamped edges. Since the actual fixity of the panel edges is not established at this time, the two extreme assumptions serve to bound the solution.

The calculations were made using the methods outlined in Reference 2-3. Specifically, strut type buckling was calculated from:

$$\sigma_{Ycr} = \frac{pi^2 EI}{AL^2} \Big/ \left(1 + \frac{pi^2 EI}{L^2 GA_s}\right)$$

where EI is the flexural rigidity of the assumed shell strip, A is its cross sectional area, and GA_s is the shear rigidity of the strip.

The panel buckling stresses were computed from :

$$\sigma_{Ycr} = \frac{2pi^2}{hb^2} [\ D_{x}y + \sqrt{D_x Dy}\ ]$$

for a long simply supported orthotropic strip, and:

$$\sigma_{Ycr} = \frac{pi^2}{hb^2} [\ 2.4D_{x}y + 4.6\sqrt{D_x Dy}\ ]$$

for a strip with clamped edges. D_x and Dy are the flexural rigidities and $D_{x}y$ is the twisting rigidity per unit width = $Gh^3/6 + uD_x$. These estimates of buckling stress should be verified by a more accurate method such as the folded plate analysis discussed in Reference 2-3, or one of the finite element plate solutions used for composite analysis. For purposes of this model design, however,they are considered to be acceptable for definition of the design problem.

2.3.2.2 Buckling Stress Levels. The results of these calculations are shown in Figures 2-10 to 2-12. For purposes of comparison, it was assumed that the longest compartment, the Auxiliary Machinery Room from frames 58 to 82, was divided in half by a suitable web frame, and that the Engine Room from frames 82 to 106 was not. As will be seen from the results in Table 2-8, the buckling stress in the longer compartment was one forth of "that for the divided compartment. If it is therefore assumed that both of these compartments are divided in half by such a frame, the critical panel will be in the Auxiliary Machinery Room, due to its location closer to the highest bending stress amidships.

FWSH - BUCKLING STRESS ANALYSIS - BOTTOM & DECK PLATING

MATERIAL PROPERTIES: BALANCED LAMINATE, 50% GLASS

YOUNG'S MODULUS = 2.30E+06
SHEAR MODULUS = 4.70E+05
POISSON RATIO = 0.12

LOADING: HULL BENDING DUE TO 4615 FT-TON (MAX) BENDING MOMENT, NO HYDROSTATIC PRESSURE.

PANEL		10 to 24	24 to 40	40 to 58	58 to 70	70 to 82	82 to 106	106 to 116	116 to 130
LENGTH-FT		14	16	18	12	12	24	10	14
SHELL WIDTH-FT		20.50	22.90	24.10	27.30	27.30	27.70	26.60	26.00
DECK WIDTH-FT.		20.00	43.40	28.00	28.80	8.00	28.00	29.00	28.40
COLUMN BUCKLING STRESS FOR SIMPLY SUPPORTED 12 IN. STRIP OF SHELL.									
HULL t, IN.	fSTIFF	Buckling Stress in PSI							
3.00	1.70E+07	602	461	365	820	820	205	1179	602
4.00	3.03E+07	1070	820	648	1455	1455	365	2093	1070
5.00	4.73E+07	1670	1279	1011	2270	2270	569	3261	1670
6.00	6.81E+07	2401	1840	1455	3261	3261	820	4682	2401
PANEL BUCKLING STRESS, BOTTOM SHELL FROM KEEL TO TURN OF BILSE.									
HULL t, IN.	E*I (b=1)	Critical Stress, Panel With Simply Supported Edges.							
3.00	5.18E+06	860	689	622	485	485	471	511	535
4.00	1.23E+07	1529	1225	1106	862	862	838	908	951
5.00	2.40E+07	2389	1915	1729	1347	1347	1309	1419	1485
6.00	4.14E+07	3441	2757	2489	1940	1940	1884	2043	2139
HULL t, IN.	E*I (b=1)	Critical Stress, Panel With Clamped Edges.							
3.00	5.18E+06	1651	1323	1195	931	931	904	981	1026
4.00	1.23E+07	2935	2352	2124	1655	1655	1608	1743	1825
5.00	2.40E+07	4586	3675	3319	2586	2586	2512	2724	2851
6.00	4.14E+07	6604	5293	4779	3724	3724	3617	3923	4106
PANEL BUCKLING STRESS, DECK FROM GUNWALE TO GUNWALE, OR BETWEEN HATCHES.									
HULL t, IN.	E*I (b=1)	Critical Stress, Panel With Simply Supported Edges.							
3.00	5.18E+06	904	192	461	436	5648	461	430	448
4.00	1.23E+07	1607	341	820	775	10041	820	764	797
5.00	2.40E+07	2510	533	1281	1211	15689	1281	1194	1245
6.00	4.14E+07	3615	768	1844	1743	22592	1844	1719	1793
HULL t, IN.	E*I (b=1)	Critical Stress, Panel With Clamped Edges.							
3.00	5.18E+06	1735	368	885	837	10842	885	825	860
4.00	1.23E+07	3084	655	1573	1487	19274	1573	1467	1529
5.00	2.40E+07	4819	1023	2458	2324	30116	2458	2292	2390
6.00	4.14E+07	6939	1474	3540	3346	43367	3540	3300	3441

FWSH - BUCKLING STRESS ANALYSIS - BOTTOM & DECK PLATING

MATERIAL PROPERTIES: BALANCED LAMINATE, 60% GLASS

YOUNG'S MODULUS = 2.80E+06
SHEAR MODULUS = 5.70E+05
POISSON RATIO = 0.11

LOADING: HULL BENDING DUE TO 4615 FT-TON (MAX) BENDING MOMENT, NO HYDROSTATIC PRESSURE.

PANEL		10 to 24	24 to 40	40 to 58	58 to 70	70 to 82	82 to 106	106 to 116	116 to 130
LENGTH-FT		14	16	18	12	12	24	10	14
SHELL WIDTH-FT		20.50	22.90	24.10	27.30	27.30	27.70	26.60	26.00
DECK WIDTH-FT.		20.00	43.40	28.00	28.80	8.00	28.00	29.00	28.40

COLUMN BUCKLING STRESS FOR SIMPLY SUPPORTED 12 IN. STRIP OF SHELL.

HULL t, IN.	fSTIFF	Buckling Stress in PSI							
3.00	2.07E+07	733	562	444	998	998	250	1436	733
4.00	3.68E+07	1303	998	789	1771	1771	444	2547	1303
5.00	5.76E+07	2033	1557	1231	2763	2763	693	3970	2033
6.00	8.29E+07	2922	2240	1771	3970	3970	998	5700	2922

PANEL BUCKLING STRESS, BOTTOM SHELL FROM KEEL TO TURN OF BILGE.

HULL t, IN.	E*I (b=1)	Critical Stress, Panel With Simply Supported Edges.							
3.00	6.30E+06	1039	833	752	586	586	569	617	646
4.00	1.49E+07	1847	1481	1337	1042	1042	1012	1097	1149
5.00	2.92E+07	2887	2313	2089	1628	1628	1581	1715	1795
6.00	5.04E+07	4157	3331	3008	2344	2344	2277	2469	2584
HULL t, IN.	E*I (b=1)	Critical Stress, Panel With Clamped Edges.							
3.00	6.30E+06	2001	1603	1448	1128	1128	1096	1188	1244
4.00	1.49E+07	3557	2850	2573	2005	2005	1948	2112	2211
5.00	2.92E+07	5557	4453	4021	3133	3133	3044	3301	3455
6.00	5.04E+07	8002	6413	5790	4512	4512	4383	4753	4975

PANEL BUCKLING STRESS, DECK FROM GUNWALE TO GUNWALE, OR BETWEEN HATCHES.

HULL t, IN.	E*I (b=1)	Crit: al Stress, Panel With Simply Supported Edges.							
3.00	6.30E+06	1092	232	557	527	6824	557	519	541
4.00	1.49E+07	1941	412	990	936	12131	990	923	963
5.00	2.92E+07	3033	644	1547	1463	18955	1547	1442	1504
6.00	5.04E+07	4367	927	2228	2106	27296	2228	2077	2166
HULL t, IN.	E*I (b=1)	Critical Stress, Panel With Clamped Edges.							
3.00	6.30E+06	2102	446	1072	1014	13136	1072	1000	1042
4.00	1.49E+07	3737	794	1906	1802	23353	1906	1777	1853
5.00	2.92E+07	5838	1240	2979	2816	36490	2979	2777	2895
6.00	5.04E+07	8407	1785	4289	4054	52545	4289	3999	4169

FWSH - BUCKLING STRESS ANALYSIS - BOTTOM & DECK PLATING

MATERIAL PROPERTIES: BALANCED LAMINATE, 70% GLASS

YOUNG'S MODULUS =	3.50E+06
SHEAR MODULUS =	7.30E+05
POISSON RATIO =	0.12

LOADING: HULL BENDING DUE TO 4615 FT-TON (MAX) BENDING MOMENT, NO HYDROSTATIC PRESSURE.

PANEL	10 to 24	24 to 40	40 to 58	58 to 70	70 to 82	82 to 106	106 to 116	116 to 130
LENGTH-FT	14	16	18	12	12	24	10	14
SHELL WIDTH-FT	20.50	22.90	24.10	27.30	27.30	27.70	26.60	26.00
DECK WIDTH-FT.	20.00	43.40	28.00	28.80	8.00	28.00	29.00	28.40

COLUMN BUCKLING STRESS FOR SIMPLY SUPPORTED 12 IN. STRIP OF SHELL.

HULL t, IN.	fSTIFF	Buckling Stress in PSI							
3.00	2.59E+07	917	702	555	1247	1247	312	1795	917
4.00	4.61E+07	1628	1247	986	2214	2214	555	3185	1628
5.00	7.20E+07	2541	1947	1539	3454	3454	867	4964	2541
6.00	1.04E+08	3653	2800	2214	4964	4964	1247	7126	3653

PANEL BUCKLING STRESS, BOTTOM SHELL FROM KEEL TO TURN OF BILGE.

HULL t, IN.	E*I (b=1)	Critical Stress, Panel With Simply Supported Edges.							
3.00	7.88E+06	1316	1055	952	742	742	721	782	818
4.00	1.87E+07	2340	1875	1693	1319	1319	1282	1390	1455
5.00	3.65E+07	3656	2930	2645	2061	2061	2002	2171	2273
6.00	6.30E+07	5265	4219	3809	2969	2969	2883	3127	3273
HULL t, IN.	E*I (b=1)	Critical Stress, Panel With Clamped Edges.							
3.00	7.88E+06	2521	2020	1824	1422	1422	1381	1497	1567
4.00	1.87E+07	4482	3592	3243	2527	2527	2455	2662	2786
5.00	3.65E+07	7003	5612	5067	3949	3949	3836	4160	4354
6.00	6.30E+07	10085	8082	7297	5687	5687	5524	5990	6269

PANEL BUCKLING STRESS, DECK FROM GUNWALE TO GUNWALE, OR BETWEEN HATCHES.

HULL t, IN.	E*I (b=1)	Critical Stress, Panel With Simply Supported Edges.							
3.00	7.88E+06	1383	294	705	667	8642	705	658	686
4.00	1.87E+07	2458	522	1254	1186	15364	1254	1169	1219
5.00	3.65E+07	3841	816	1960	1852	24006	1960	1827	1905
6.00	6.30E+07	5531	1175	2822	2667	34569	2822	2631	2743
HULL t, IN.	E*I (b=1)	Critical Stress, Panel With Clamped Edges.							
3.00	7.88E+06	2643	563	1351	1277	16555	1351	1260	1314
4.00	1.87E+07	4709	1000	2403	2271	29432	2403	2240	2335
5.00	3.65E+07	7358	1563	3754	3548	45987	3754	3500	3649
6.00	6.30E+07	10595	2250	5406	5110	66221	5406	5039	5255

Table 2-8

SUMMARY OF CRITICAL BUCKLING STRESSES - 60% GLASS

Bending and Buckling Stresses - Auxiliary Machinery Room								
Laminate Thickness (Hull/Deck)	3/3	3/2	4/4	4/3	5/5	5/4	6/6	6/5
Hull Bending Stress: Keel, psi	439	460	330	340	263	270	219	224
Deck, psi	370	475	278	333	222	256	185	208
<u>Critical Buckling Stress, FR 58-70:</u>								
(A) Edges Simply Supported: Keel	586	-	1042	-	1628	-	2344	-
Deck	527	-	936	-	1463	-	2106	-
(B) Edges Clamped: Keel	1128	-	2005	-	3133	-	4512	-
Deck	1014	-	1802	-	2816	-	4054	-
(C) Average of (A) and (B): Keel	857	-	1524	-	2381	-	3428	-
Deck	771	-	1369	-	2140	-	3080	-
Design Factor = $\frac{\text{Buckling Stress}}{\text{Hull Comp. Stress}}$: Keel	2.0	-	4.6		9.1		15.7	
Deck	2.1	-	4.9		9.6		16.7	

<u>For Buckling Reserve Factor = 4:</u>

Required hull thickness = 3.8 in.
Required deck thickness = 3.7 in.

For an assumed 60% glass winding, and for a buckling limit midway between the two edge conditions, the stress resulting from hull bending compares with the critical stress for the various hull thicknesses as shown in Table 2-8. It will be seen from these results that allowable working stresses are on the order of 300 psi, based on a reserve factor of 4 over the computed buckling stresses of about 1200 psi. This compares to a buckling allowable of about 11,000 psi and working stress of about 3,000 psi for the British HMS Wilton design(2-9), with a 1.63 inch thick shell and 5x10 inch transverse frames on 24 to 27 inch centers. If the material in the transverse frames is smeared onto the shell thickness for equivalent weight purposes, the result is an additional 1.13 inches, for a total equivalent bottom shell thickness of 2.76 inches, not including girders and brackets. Thus the penalty in hull weight due to the low buckling resistance of the monocoque structure is approximately the difference between 4.1 and 2.8 inches, or 46%. If the modulus of the laminate can be increased by the addition of some Kevlar or carbon fibers to the matrix, or by increasing the percentage of reinforcement to resin, this difference could be reduced. The use of longitudinal stiffeners would also reduce the shell weight, of course, but would defeat the advantage of monocoque construction. One possible way around this problem would be to pre-manufacture the longitudinal framing and incorporate it into the mandrel while still in a "B-stage" or uncured state, so that it would cure at the same time as the shell winding and result in a primary bond attachment. Such a joint might still require secondary mechanical fastening in order to resist explosive loading. If effective ring frames or web frame attachments can be wound into the hull as part of the fabrication process, this would also reduce the weight by increasing the buckling limits. Another possibility for future investigation in the use of lower weight/strength reinforcement materials in the center of the laminate to increase its buckling stiffness and allow higher working stresses. This is

similar in concept to sandwich construction, except that the density and strength could be varied in a controlled manner, as opposed to a sudden change of characteristics at a core bond line.

2.3.3 Underwater Explosion (UNDEX) Pressure Stresses

The quasi-static pressure value of 29.3 PSI was used to investigate shell stress and scantlings for the entire length of ship, using the bulkhead spacings from the concept MSH minehunter arrangement drawing, along with dimensions taken from the concept lines drawing. As mentioned in the previous section on hull bending stress, attempts to use the MCM-1 lines appeared to result in misleading answers due to the greater fineness of that hull design when scaled down to the MSH size. In the case of the UNDEX loads, the narrower hull would have resulted in smaller transverse panel dimensions, leading to an optimistic structural solution.

The first calculation was for a 1 inch wide strip of shell running longitudinally, with the ends assumed fixed at the bulkheads to simulate the effect of equal pressure loading distribution on each side of the bulkhead location. This is of course a conservative calculation in terms of no edge support for the strips. For comparison to this assumption, another calculation was made of the stress and deflection of the bottom panels assuming the same fixity at the bulkheads, but with the panel edges simply supported at the keel and bilge. This is a reasonable assumption for the case where the UNDEX pressure is originating from one side of the ship, as opposed from directly underneath, since one side of the bottom panel sees the pressure loading before it is balanced by equal loading on the other side of the keel. At the bilge, the assumption of simple support emulates rotation of the panel edge about a node point near the bilge keel. This node results from

the increased stiffness of the curved bilge plating in longitudinal bending, but there is no significant resistance to transverse rotation of the panel about this node line.

The results of these calculations are shown in Figures 2-13 through 2-15. The 1 inch wide strip calculation was made using simple beam theory, and the plate calculation according to isotropic flat plate theory using the factors from Roark, case 43, page 227.[2-12] If we assume, as in the case of the buckling stress analysis, that the two long machinery compartments are divided in half by a web or ring frame, then the longest and therefore critical compartment is the water tank forward of the machinery spaces, frames 40 to 58. The flat panel calculation results in only a slightly lower stress level than the simple strip calculation, but the deflection is appreciably lower, 3.3 inches compared to 4.0 for the strip, for a 6.0 inch thick shell of 50% glass. It will be recalled from Section 2.3.2 that the required shell thickness for buckling was about 4.1 inches, based on a 60% glass content. The stress from UNDEX pressure for the same hull scantling is seen from Figure 2-14 to be about 41 ksi, compared to a flexural ultimate of 30 to 40 Ksi for the best hand layup roving hulls tested to date.

If it is assumed that stiffeners or revised bulkhead locations reduced the span of the plate to that of the divided machinery compartments, or 12 feet, then the resultant bending stress is reduced to 19 ksi, and the deflection from 9.2 to 2.0 inches. If the shell thickness is increased to 6 inches, the stress and deflection for the 12 foot spacing are reduced to 8.4 ksi and 0.6 inches, respectively. If an ultimate flexural stress value of 40 ksi is assumed for the 60% glass, this would result in a design factor of 4.76, compared to the assigned design factor of 4. If a flexural strength of 60 ksi is assumed, then a hull thickness of about 4.5 inches would be required, resulting in a deflection in

FWSH - BOTTOM PANEL STRESS DUE TO QUASI-STATIC UNDEX PRESSURE

MATERIAL PROPERTIES: BALANCED LAMINATE, 50% GLASS

YOUNG'S MODULUS = 2.30E+06
SHEAR MODULUS = 4.70E+05
POISSON RATIO = 0.12

PRESSURE, PSI =29.3

BENDING STRESS AND DEFLECTION DUE TO PRESSURE LOAD

PANEL	10 to 24	24 to 40	40 to 58	58 to 70	70 to 82	82 to 106	106 to 116	116 to 130
LENGTH-FT	14	16	18	12	12	24	10	14
WIDTH-FT	20.5	22.9	24.1	27.3	27.3	27.7	26.6	26.0
a/b=w/l	1.46	1.43	1.34	2.28	2.28	1.15	2.66	1.86
BETA	0.4910	0.4882	0.4806	0.4976	0.4976	0.4540	0.4980	0.4973
ALPHA	0.02658	0.02641	0.02571	0.02843	0.02843	0.02357	0.02847	0.02812
MOMENT - IN.LB.	68914	90010	113918	50630	50630	202522	35160	68914

STRESS FOR 1 IN. WIDE STRIP, FIXED ENDS (PRESSURE EXTENDS OVER ADJACENT PANELS)

HULL t, IN.	Stress in PSI							
3	45942	60006	75946	33754	33754	135014	23440	45942
4	25843	33754	42719	18986	18986	75946	13185	25843
5	16539	21602	27340	12151	12151	48605	8438	16539
6	11486	15002	18986	8438	8438	33754	5860	11486

DEFLECTION FOR 1 IN. WIDE STRIP, FIXED ENDS

HULL t,IN.	Deflection in inches							
3	11.75	20.04	32.10	6.34	6.34	101.44	3.06	11.75
4	4.96	8.45	13.54	2.67	2.67	42.79	1.29	4.96
5	2.54	4.33	6.93	1.37	1.37	21.91	0.66	2.54
6	1.47	2.50	4.01	0.79	0.79	12.68	0.38	1.47

STRESS FOR FLAT PLATE, FIXED AT BULKHEADS, SUPPORTED AT KEEL AND BILGE.

HULL t, IN.	Stress in PSI							
3	45115	58590	72999	33592	33592	122593	23346	45694
4	25377	32957	41062	18895	18895	68959	13132	25703
5	16242	21092	26280	12093	12093	44134	8405	16450
6	11279	14648	18250	8398	8398	30648	5837	11424

DEFLECTION FOR FLAT PLATE

HULL t, IN.	Deflection in inches							
3	9.99	16.93	26.41	5.77	5.77	76.51	2.79	10.57
4	4.21	7.14	11.14	2.43	2.43	32.28	1.18	4.46
5	2.16	3.66	5.70	1.25	1.25	16.53	0.60	2.28
6	1.25	2.12	3.30	0.72	0.72	9.56	0.35	1.32

FWSH - BOTTOM PANEL STRESS DUE TO QUASI-STATIC UNDEX PRESSURE

MATERIAL PROPERTIES: BALANCED LAMINATE, 60% GLASS

YOUNG'S MODULUS = 2.80E+06
SHEAR MODULUS = 5.70E+05
POISSON RATIO = 0.11

PRESSURE, PSI =29.3

BENDING STRESS AND DEFLECTION DUE TO PRESSURE LOAD

PANEL	10 to 24	24 to 40	40 to 58	58 to 70	70 to 82	82 to 106	106 to 116	116 to 130
LENGTH-FT	14	16	18	12	12	24	10	14
WIDTH-FT	20.5	22.9	24.1	27.3	27.3	27.7	26.6	26.0
a/b=w/l	1.46	1.43	1.34	2.28	2.28	1.15	2.66	1.86
BETA	0.4910	0.4882	0.4806	0.4976	0.4976	0.4540	0.4980	0.4973
ALPHA	0.02658	0.02641	0.02571	0.02843	0.02843	0.02357	0.02847	0.02812
MOMENT - IN.LB.	68914	90010	113918	50630	50630	202522	35160	68914

STRESS FOR 1 IN. WIDE STRIP, FIXED ENDS (PRESSURE EXTENDS OVER ADJACENT PANELS)

HULL t, IN.	Stress in PSI							
3	45942	60006	75946	33754	33754	135014	23440	45942
4	25843	33754	42719	18986	18986	75946	13185	25843
5	16539	21602	27340	12151	12151	48605	8438	16539
6	11486	15002	18986	8438	8438	33754	5860	11486

DEFLECTION FOR 1 IN. WIDE STRIP, FIXED ENDS

HULL t, IN.	Deflection in inches							
3	9.65	16.46	26.36	5.21	5.21	83.32	2.51	9.65
4	4.07	6.94	11.12	2.20	2.20	35.15	1.06	4.07
5	2.08	3.56	5.69	1.12	1.12	18.00	0.54	2.08
6	1.21	2.06	3.30	0.65	0.65	10.42	0.31	1.21

STRESS FOR FLAT PLATE, FIXED AT BULKHEADS, SUPPORTED AT KEEL AND BILGE.

HULL t, IN.	Stress in PSI							
3	45115	58590	72999	33592	33592	122593	23346	45694
4	25377	32957	41062	18895	18895	68959	13132	25703
5	16242	21092	26280	12093	12093	44134	8405	16450
6	11279	14648	18250	8398	8398	30648	5837	11424

DEFLECTION FOR FLAT PLATE

HULL t, IN.	Deflection in inches							
3	8.21	13.91	21.69	4.74	4.74	62.85	2.2[illegible]	8.68
4	3.46	5.87	9.15	2.00	2.00	26.51	0.97	3.66
5	1.77	3.00	4.69	1.02	1.02	13.57	0.49	1.88
6	1.03	1.74	2.71	0.59	0.59	7.86	0.29	1.09

FWSH - BOTTOM PANEL STRESS DUE TO QUASI-STATIC UNDEX PRESSURE

MATERIAL PROPERTIES: BALANCED LAMINATE, 70% GLASS
YOUNG'S MODULUS = 3.50E+06
SHEAR MODULUS = 7.30E+05
POISSON RATIO = 0.12
PRESSURE, PSI =29.3

BENDING STRESS AND DEFLECTION DUE TO PRESSURE LOAD

PANEL	10 to 24	24 to 40	40 to 58	58 to 70	70 to 82	82 to 106	106 to 116	116 to 130
LENGTH-FT	14	16	18	12	12	24	10	14
WIDTH-FT	20.5	22.9	24.1	27.3	27.3	27.7	26.6	26.0
a/b=w/l	1.46	1.43	1.34	2.28	2.28	1.15	2.66	1.86
BETA	0.4910	0.4882	0.4806	0.4976	0.4976	0.4540	0.4980	0.4973
ALPHA	0.02658	0.02641	0.02571	0.02843	0.02843	0.02357	0.02847	0.02812
MOMENT - IN.LB.	68914	90010	113918	50630	50630	202522	35160	68914

STRESS FOR 1 IN. WIDE STRIP, FIXED ENDS (PRESSURE EXTENDS OVER ADJACENT PANELS)

HULL t, IN.	Stress in PSI							
3	45942	60006	75946	33754	33754	135014	23440	45942
4	25843	33754	42719	18986	18986	75946	13185	25843
5	16539	21602	27340	12151	12151	48605	8438	16539
6	11486	15002	18986	8438	8438	33754	5860	11486

DEFLECTION FOR 1 IN. WIDE STRIP, FIXED ENDS

HULL t,IN.	Deflection in inches							
3	7.72	13.17	21.09	4.17	4.17	66.66	2.01	7.72
4	3.26	5.55	8.90	1.76	1.76	28.12	0.85	3.26
5	1.67	2.84	4.56	0.90	0.90	14.40	0.43	1.67
6	0.96	1.65	2.64	0.52	0.52	8.33	0.25	0.96

STRESS FOR FLAT PLATE, FIXED AT BULKHEADS, SUPPORTED AT KEEL AND BILGE.

HULL t, IN.	Stress in PSI							
3	45115	58590	72999	33592	33592	122593	23346	45694
4	25377	32957	41062	18895	18895	68959	13132	25703
5	16242	21092	26280	12093	12093	44134	8405	16450
6	11279	14648	18250	8398	8398	30648	5837	11424

DEFLECTION FOR FLAT PLATE

HULL t, IN.	Deflection in inches							
3	6.56	11.13	17.35	3.79	3.79	50.28	1.83	6.95
4	2.77	4.69	7.32	1.60	1.60	21.21	0.77	2.93
5	1.42	2.40	3.75	0.82	0.82	10.86	0.40	1.50
6	0.82	1.39	2.17	0.47	0.47	6.28	0.23	0.87

the 12 foot compartment of about 1.5 inches. This selection is discussed further in Section 2.4.

2.3.4 Bulkhead Stresses

The bulkheads are designed to resist a head of water to 4 feet below the weather deck, based on flooding of an adjacent compartment. It was assumed that the bulkheads would be of sandwich construction, in accordance with the general concept of maximum automation and minimum manhours. The minesweeper test section[2-14], one of the alternate designs for HMS Wilton [2-7], and the Tripartite minesweeper program have all evaluated bulkhead designs using woven roving GRP faces over a balsa or foam core. An additional consideration was the difficulties experienced in the MOD testing for the MCMV, where the attachment of the tapered ends of the bulkhead stiffeners near the shell was shown to be prone to debonding under extreme load, making the elimination of secondary bonded stiffeners a desirable objective.

The major problem with the use of a sandwich bulkhead design will be the abillity to absorb and transmit UNDEX loads from the hull, and it is not clear at this time if that can be succesfully accomplished. Since the model will not be tested for UNDEX loads, however, it is felt that the use of a bulkhead sandwich will reduce costs and construction complexity, and is desirable for that reason.

2.3.4.1 Sandwich Panel Analysis. Methods for analyzing sandwich structural panels are given in Mil-Handbook-23A.[2-18] A set of nomograms based on these methods was developed by the Balsa Ecuador Lumber Company[2-19] for use in designing structural panels using end grain balsa as a core, but are applicable to other materials. These nomograms were used to provide a preliminary estimate of the scantlings required for the subject bulk-

heads. The bulkhead between the machinery spaces was selected as the most critical for design, based on its dimensions. Stresses were calculated for a 12 inch wide vertical strip, assuming simple supports at the shell and main deck, and assuming a uniform load equal to the (average) head at 1/2 the height of the bulkhead up to the main deck, or 12/2 + 4 = 10 feet. This assumption was used to allow applying a uniform loading, thus simplifying the calculations. This was considered acceptable accuracy for a concept design such as this, but a more accurate calculation would be required for a preliminary ship design when better material allowables data would justify the improved accuracy.

2.3.4.2 Analysis Results The nomographs for beam stress and deflection gave the results shown in Table 2-9, assuming a 5 inch thick core, and 1/2 inch skins of woven roving GRP. The average head at the mid-height of the bulkhead is 10 feet, resulting in an average load of 4.44 psi. The resultant bending stress is 5200 psi, and the core shear stress is 115 psi. Bending deflection is 4.0 inches , or 1/36 of the span, which is excessive. The bending stiffness or flexural rigidity given by the nomograph was checked according to the formula and factor given in Figure 1-3 of MIL-HDBK-23a, and was shown to be correct.

The nomographs were then used to check the bulkhead stress and deflection assuming the bulkhead to be a flat plate simply supported at the bottom shell, side shell, and main deck. The results were then compared with the simple beam assumption case. These results are also shown in Table 2-9. It will be seen that the plate calculation, although it is in effect for an infinitely long plate, still yields lower stress and deflection results than the assumption of a 12 inch wide strip. It is considered to be more accurate, since the beam calculation required interpolation beyond the limits of the nomograph. The plate analysis resulted in a material strength requirement of about 15 Ksi in bending for

Table 2-9

SANDWICH BULKHEAD STRESS AND DEFLECTION

Calculation	Bending Stress (psi)	Shear Stress in Cone (psi)	Deflection (in.)
(A) 12-in. Wide Beam, Simple Supports	5200	115	4.0
(B) Flat Panel, a/b $=\alpha$, Simple Supports	3690	125	2.0
(C) Required Material Properties - Ultimate	3,690 x 4 = 14,760	125 x 4 = 500	(1/72 span)

Note: Calculations are for bulkhead at Frame 82.
Loading assumed: Uniform pressure equal to head at 1/2 of bulkhead height.

$E_{GRP} = 2.0 \times 10^6$

$t_c = 5$ in.

$t_f = 0.5$ in.

$b = 144$ in.

$a/b = \alpha$

$w = 4.44$ psi

the GRP faces, and 500 psi in shear for the core. Since this is less than the minimum compressive ultimate of 21 Ksi found in the Peterson/Owens-Corning test panels,[2-15] and close to the shear ultimate reported by the manufacturer for 12 lb/cu ft Divinycell PVC (polyvinyl chloride) structural foam, it is deemed to adequate for the purposes of this study. The manufacturers of Klegecell PVC foam report lower numbers for the same material, and so these values would have to be investigated further before accepting these sandwich proportions for a ship design. End grain balsa of about 8 lb/cu ft density has a shear ultimate of about 250 psi, and would therefore appear to be inadequate for this bulkhead design. On the other hand, the minesweeper test section built by Peterson[2-14] used two layers of this balsa to form a 5 inch thick core for the bulkheads in that, with a similar design loading. It was therefore felt that this design was adequate for the current effort, and it can be easily modified before construction of the model if desired. For purposes of the model design, when scaled from the 5 inch + 0.5 inch down to the 1/5 scale model size, actual core thickness will be determined by material availability, and will therefore have to be selected on that basis, with the skin thicknesses adjusted to suit. This is discussed further in Sections 2.4 and 2.5.

2.3.5 Secondary Hull Loading Stresses

In addition to the primary stresses due to hull bending, UNDEX pressures, and compartment flooding, the design loads specified secondary hydrostatic hull loads of:

(a) Full load draft + $0.55\sqrt{L}$ = 6.45 psi

(b) Head due to 35' heel at full load draft = 5.33 psi

(c) 500 psf = 3.47 psi

and for the deck:

(a) 4 foot hydrostatic head = 1.78 psi

Because of the low buckling stress problems, discussed in Section

2.3.2, and the high UNDEX pressure loads, none of these secondary loads is significant to the design of the structure. As was noted in Section 2.3.2, a shell thickness of about 4.1 inches resulted in a bending stress of about 330 psi against a buckling limit of about 1200 psi, and the UNDEX pressure of 29.3 psi resulted in a bending stress at the same thickness of about 19 Ksi, and at a thickness of 6 inches about 8.4 Ksi. Thus the maximum secondary load of about 6.5 psi at the keel is only about 20% of the load due to UNDEX, and would not affect the design. Similarly, the secondary deck loading and topsides wave slap load of 3.5 psi would not affect the required thickness of the deck due to buckling, or the thickness of the topsides, since they would be at least to some degree related to the thickness of the bottom and deck in a filament wound design. It is possible, of course, that the topsides could be somewhat thinner, and the bottom and deck increased in thickness by the addition of extra layers of laminate oriented in the direction of principal stress, but without a detailed finite element analysis to evaluate the stress distribution in the topsides, it is recommended that their scantlings be similar to the remainder of the hull, with the exception of a few layers of material added to the deck and bottom to develope and demonstrate the techniques for doing so.

On other point that should be mentioned at this time is that the calculations for critical buckling stress did not take into account the static pressure head of 3.6 psi due to the 8 foot draft. Of course, the presense of any transverse pressure load lowers the resistance of the panel to buckling, and this should be taken into account in a more rigorous finite element solution of the biaxial stress distributions and buckling problem, as pointed out by Smith.[2-3] For purposes of this study, however, the UNDEX bending stress still predominates the design.

2.4 FULL SCALE SHIP SCANTLINGS

Based on the materials allowables examined in Section 2.2, and the stress analysis discussed in 2.3, recommended scantlings were adopted for use in determining the design of the 30 foot model, as follows:

(a) Bottom shell amidships	5.0"
(b) Deck amidships	4.0"
(c) Topsides amidships	3.0"
(d) Ends of ship (.1L)	0.8 x $t_{midships}$

The reductions in thickness on the topsides and at the ends are nominal, and designed to provide demonstration of techniques for tapering the thickness of a filament wound hull. They are not based on stress calculations.

2.5 SCALING & MODEL SCANTLINGS

As discussed in Section 2.0, the scantlings were scaled down to model size on a purely geometric basis, based on the lengths of the ship and model. This results in the basic laminate thicknesses for the model as follows:

(a) Bottom shell amidships	1.0"
(b) Deck amidships	0.8"
(c) Topsides amidships	0.6"
(d) Ends of model (.1L)	0.8 x $t_{midships}$

These thicknesses, along with approximately scaled fiber band thickness as discussed in Section 4.4.3, will yield a laminate that is a scale representation of the full size ship as currently envisioned. As will be discussed in Section 4, it is possible that considerations of developing a resin system that is suitable for the winding of thick sections will make it appropriate to use greater thicknesses in the model.

REFERENCES - SECTION 2

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2-2	"An Evaluation of The Strength Under Lateral Load of Small-Scale Glass-Reinforced Plastic Beams Representing The MCMV Bulkhead Structure", J. W. Swan & W. L. Somerville, Report No. NCRE/N224, Naval Construction Research Establishment, Dunformline, Scotland, September 1974.
2-3	"Buckling Problems In The Design of Fiberglass-Reinforced Plastic Ships", C. S. Smith, Journal of Ship Research, September 1972, P. 174-190.
2-4	"The Testing of Mine Countermeasures Vessel Structures", J. Charles Worth, NCRF Report # R559, Naval Construction Research Establishment, Dunfermline, Scotland, May, 1970.
2-5	"Large Ships of Glass Reinforced Plastics", "Composites" Magazine, September 1969, PP. 52-53.
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2-7	"Design and Build of the GRP Hull of the HMS Wilton", R.H. Dixon, B. W. Ramsey, P. J. Usher, Proceedings of the Symposium on GRP Ship Construction, Royal Institution of Naval Architects, London, October 1972.
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2-15 "Final Technical Report, Glass Reinforced Plastic Minesweeper Test Section", Peterson Builders, Inc., Sturgeon Bay, Wisconsin, January 1970, AD-871130.

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2-18 "MIL-HANDBOOK-23A, Structural Sandwich Composites, Dept. of Defense, Washington, D.C. 20025, 1968.

2-19 "Structural Sandwich Nomograms", R. R. Desai, Design News, October 1971.

2-20 "The Hunt Class Mine Countermeasures Vessels", A. J. Harris, Proceeding of the Royal Institute of Naval Architects, 1980, Pg. 485.

NUMBER TITLE

2-21 "Design of High Performance Hulls in Fiber-Reinforced Plastics", C. S. Smith and A. H. Monks, RINA Symposium on Small Fast Warships and Security Vessels, 18 May 1982, Paper No. 8.

SECTION 3
MATERIALS

This section describes the review and evaluation of materials which was performed in order to identify the candidate materials which might be suitable for building a filament wound ship hull. Both reinforcement fiber materials and matrix resin materials were reviewed in terms of: (1) their properties, (2) available performance data and experience, (3) the projected requirements for both a filament wound ship hull and a 1/5 scale model of such a hull, and (4) the specific requirements of filament winding. Based on this review, materials were selected for the 30 foot (1/5 scale) model, including both baseline and alternate suggested materials. Resulting materials and process requirements were prepared in the form of "Proposed Requirements" documents for the materials, the process, and a separate document for the resin. These specifications are included as Appendix B to this report, and are discussed in more detail in the following sections.

3.1 REVIEW OF CANDIDATE MATERIALS

This section will review the candidate reinforcements and matrix resins currently used for boat construction by the Navy, along with others which were considered because they offered the possibility of improved performance for a filament wound ship hull.

3.1.1 Reinforcements

The reinforcement for marine composite structures has traditionally been the glass fiber known in the trade as E glass, available as roving bundles, woven cloth, woven roving, stitched or knitted unidirectional roving, and random fiber mat or "matte". More recently, boats have been built using Kevlar (TM) Aramid

fiber fabric, carbon fiber in fabric or "tow" (parallel filament tape) form, and some other synthetic fabrics such as Dacron (TM), and Dynel (TM). In the aircraft and aerospace industries, S Glass, more recently S-2 Glass, carbon, Kevlar, and boron are used as reinforcements, generally in the form of preimpregnated tape or cloth. Each of these reinforcements will be discussed in the following subsections.

3.1.1.1 E Glass Reinforcements. E Glass has traditionally been used with room temperature cure polyester resins for boat building. It has a finish on the fibers which was developed specifically for polyester resin compatibility, and to provide resistance of the resin/fiber bond to degradation under moist conditions. This material is available in several forms which meet the requirements of U.S. Military specifications, specifically:

Roving, Glass, Fibrous (etc)	- MIL-R-60346
Mats, Reinforcing, Glass Fiber	- MIL-M-43243
Cloth, Glass, Finished, for Resin Laminates	- MIL-C-9048

Newer forms of these materials include unbalanced and uni-directional roving fabrics, which are stitched or knitted together to form a fabric with the desired directional properties.

One of the major advantages of E Glass is the cost, which is the lowest of any of the commonly used reinforcements. Owens/Corning is currently quoting the base material price as 1 - 2 $/lb for E Glass, compared to 3 - 4 $/lb for S-2 Glass and 11 - 12 $/lb for MIL-SPEC S Glass. Kevlar fiber cost is in the same general range as S Glass.

Most of the experience with filament wound glass products is with S Glass and E Glass. Most of the basic E Glass filament winding roving now supplied by Owens/Corning is designated as "Type 30",

and is a single end roving as opposed to the multi-strand roving used in the past and in S Glass. This material can be given a number of surface finishes, depending on the resin system and applicable MIL-SPEC. The selection of single or multi-strand roving will depend on the required yield (yards of roving per pound). Of course, either the single end (strand) or multi-end roving can be combined to form roving bundles of the desired size. It is anticipated that the Type 30 single end roving might result in a higher glass content laminate, since the greater surface area of the increased number of smaller size filaments in the conventional multi-strand roving may require slightly more resin to completely wet the filaments. This can only be established by winding and testing samples of both materials.

3.1.1.2 S Glass and S-2 Glass Reinforcements. The S Glass which has traditionally been used for MIL-SPEC aerospace and aircraft applications is a higher strength and cost fiber than the E-Glass used in the marine industry. The difference in chemical content of the S and E Glass materials is shown in Table 3-1. Typical strength properties of the two fibers are shown in Table 3-2. It will be seen that the major advantage of the S Glass is a 35-40% increase in tensile strength, and an 18-20% increase in Young's modulus. Since, as was discussed in Section 2.0, the major design load for a GRP ship relate to stiffness and buckling limits, the higher modulus is of more interest than the higher strength. If used with a tougher resin system that permitted strains to the limit of the glass fiber, the greater elongation of the S Glass could also be of interest. These higher mechanical properties, particularly tensile strength, led to the use of S Glass for aerospace structures, but the only remaining Owens-Corning production of S Glass is in fact devoted to material for missile bodies. Many aircraft applications are now utilizing the newer S-2 Glass, which is priced much closer to E Glass, as mentioned above. It has the same chemical composition as S

Table 3-1

CHEMICAL COMPOSITION OF S GLASS AND E GLASS FIBERS

Compound	Percentage	
	E Glass	S Glass
Silicon oxide	54.3	64.2
Aluminum oxide	15.2	24.8
Calcium oxide	17.2	0.01
Magnesium oxide	4.7	10.27
Sodium oxide	0.6	0.27
Boron oxide	8.0	0.01
Ferrous oxide	-	0.21
Barium oxide	-	0.20

Table 3-2

PROPERTIES OF S GLASS AND E GLASS FIBERS

Property	E	S & S2
Density (lb/cu in.)	0.094	0.090
Tensile Strength (Kpsi)	500	665
Modulus of Elasticity (Msi)	10.5	12.6
Ultimate Elongation, % (72^{o}F)	4.8	5.4
Coeff. of Thermal Expan. (in./in./^{o}F)	2.8 x 10-6	3.1 x 10-6

Glass, but is produced to more tolerent specifications and a different surface finish than the MIL-SPEC S Glass. It was originally developed in 1966-68, but has seen significant use in the aerospace industry only in the last 10 years or so. Whereas S Glass has traditionally been used with epoxy resin systems to develope maximum laminate properties, the S-2 Glass is now available with an experimental surface finish compatible with polyester and vinyl ester resins, as well as another one for epoxy resin systems.

Since S Glass does not have a suitable finish for marine applications with polyester resin systems, it is not possible to comment on its performance compared to E Glass in a long term moist atmosphere. The manufacturer believes there should be no significant difference in moisture resistance, but since this is to a large extent a function of the surface coating performance in bonding with the resin system, tests will be required along with significant field experience before this can be stated to be a fact. Data on epoxy/S-2 Glass laminates in NOL ring short beam shear tests and NOL ring hydroburst tests show the S-2 to have better laminate tensile properties than E Glass epoxy laminates, including post-168 hour boil test properties. Short beam shear strengths of S, S-2, and E Glass in epoxy laminates are similar. Similar data should be developed for polyester and vinyl ester laminates, to determine whether the additional cost of S-2 Glass over E Glass is warranted for an application such as a minesweeper hull. It is possible, if UNDEX loaded panel bending is the critical stress, that S-2 Glass should be considered as a method of reducing required hull thickness, weight, and cost.

3.1.1.3 Kevlar Aramid Reinforcements. Increasing amounts of Kevlar aramid fiber are being used in a variety of applications, from tire cords to sailcloth and aircraft laminates. The cost per pound is similar to that of S Glass, and about an order of

magnitude greater than E Glass. Since the modulus of Kevlar is not much greater than glass, and its shear strength in a laminate is less, it is not a good candidate for the principal reinforcement in a ship hull. Kevlar's somewhat increased tensile strength and impact resistance, however, suggest that it might be considered near the exterior surface of the laminate for impact resistance, and in high wear areas such as decks for its high abrasion resistance. Kevlar is lighter than glass, and so on a weight equivalent basis has been reported as having significantly higher strength and stiffness. Because it has a lower compressive strength, its flexural strength in a resin matrix laminate is actually lower than GRP. Exact comparisons are difficult due to differences in cloth style and weave. In pleasure boat applications, Kevlar and glass have been mixed with apparently successful results, but no reliable engineering data is available to demonstrate exactly what physical properties result. An interesting comparison of different woven cloth/epoxy laminates was provided to Owens/Corning by Fiberite Corporation, and showed the following comparisons:

Property	Glass	Kevlar
(a) Tensile Strength-ksi	72	82
(b) Tensile Modulus-Msi	4.3	6.1
(c) Flexural Strength-ksi	97	69
(d) Flexural Modulus	3.8	4.8
(e) Short Beam Shear-ksi	7.5	4.0
(f) Cost - $/yard	5	18

The advantages of Kevlar are reduced when combined with polyester resin systems. Kevlar/epoxy laminates have shown better fatigue strength characteristics than E Glass or S Glass epoxy laminates, but no data is available to show if that is the case with polyester.

As stated previously, impact tests with Kevlar laminates have

shown better resistance to cracking and delaminating than glass reinforcements in the same resin. It would be valuable to examine the relative impact performance using the newer rubber toughened isophthalic polyester resins or vinyl ester resins, which have themselves been shown to increase the impact resistance of glass reinforced panels due to their higher strain capability.

In summary, the lower weight, higher stiffness, and increased toughness or impact resistance of Kevlar makes it interesting for a variety of applications. Epoxy resins are required to fully achieve these advantages, however, and the lower compressive and shear strength along with the higher cost compared to E Glass, indicate that consideration of Kevlar in a filament wound ship hull model should be limited to areas of high wear or impact loading.

3.1.1.4 Carbon/Graphite Reinforcements. The various forms of carbon fiber or graphite have been extensively used with epoxy resins to form high strength laminates for aerospace and aircraft applications. The high strength and stiffness of the fibers, when combined with the good shear properties of an epoxy resin system, result in a laminate of superior characteristics. The carbon 'tows', or loosely bonded tapes of parallel fibers, are very expensive, however. They are in the range of 18-50 $/lb, compared to 1-2 $/lb for E Glass, and thus would be prohibitively expensive as the major reinforcement for a ship hull. The major advantages of carbon fiber are its high strength and stiffness. The fiber tensile strength of carbon fiber ranges from about 300 to 550 ksi, depending on the material and testing method, compared to about 500 ksi for E Glass and 665 ksi for S Glass. The Young's modulus of the carbon fiber can range from 30 to 60 Msi, compared to 10.5 for E Glass and 12.6 for S Glass, and this stiffness is one of the major advantages of carbon fiber. Com-

pressive strength of carbon fiber/epoxy laminates is almost as high as the tensile strength, whereas in glass/epoxy laminates it is apt to be about 25% less than tension. Stiffness of carbon-/epoxy laminates at room temperature is about 6 times greater than glass/epoxy laminates, and it is this characteristic that is of principal interest in the design of a filament wound ships hull.

Since the major problem identified in the design of a large fiber reinforced plastic hull is the low stiffness of glass reinforced polyester, it has occured to many that a hybrid mixture of low cost/low stiffness fibers with a small percentage of higher stiffness/higher cost fibers might result in a laminate with superior characteristics. For instance, tests run by the Fiberite Corporation showed the following relative characteristics for laminates of woven cloth in epoxy resin:

PROPERTY	GLASS	CARBON	50/50
(a) Tensile Strength, ksi	72	82	56
(b) Tensile Modulus, Msi	4.3	10.3	7.5
(c) Flexural Strength, ksi	97	87	103
(d) Flexural Modulus, Msi	3.8	8.9	7.3
(e) Short beam shear, ksi	7.5	8.5	9.0

Other tests by a boat builder attempting to stiffen the hull of a 46 ft sailboat showed the following comparisons for a small hand layup fiberglass beam compared to one containing about 20% carbon fiber by volume:

	Glass Cloth/ Resin	Glass Cloth/Carbon Fiber/Resin
(a) Density	0.059	0.051
(b) Flexural Strength, ksi	21	41
(c) Flexural Modulus, Msi	1.7	4.4

Testing carried out by Great Lakes Research Corporation for the same project reported the results shown in Table 3-3 for press

Table 3-3

RELATIVE PROPERTIES OF GLASS, GRAPHITE, AND MIXED REINFORCEMENT LAMINATES

Material	Flexural Strength-Ksi	Flexural Modulus-Msi	Specific Gravity	Strength/S.G. Ratio - Ksi	Stiffness/S.G. Ratio - Msi
E-Glass/Polyester (a)	165	5.7	1.95	85	2.9
E-Glass/Carbon/Epoxy	151	10.5	1.70	89	6.2
Graphite/Polyester	143	17.5	1.50	95	11.7
Graphite/Polyester	152	21.0	1.55	98	13.5
Graphite/Epoxy	170-190	29.0	1.60	119	18.1

molded bars containing about 60% (volume) reinforcement fibers. It is interesting to note that the all glass cloth beam failed in compressive buckling of the outer plies, and the beam with alternate plies of glass cloth and unidirectional carbon fiber failed (at a higher stress) on the tensile side, with no evidence of buckling failure. This indicates that the carbon fiber was indeed able to carry loading applied through interlaminar shear between the different materials. The results for a filament wound structure might well be between those for the hand layup beam discussed above and the press molded beam, but some preliminary testing on filament wound structures to indicate the potential of such an approach would be useful.

One of the questions in applying such a technique to the winding of a minesweeper hull would be the effect of any carbon fiber content on the conductivity and therefore signature characteristics of the hull. This could only be determined by test, since it will depend on the amount and location of the fiber. For other applications, this conductivity would probably not be a consideration.

3.1.2 RESINS & CURE SYSTEMS

The matrix resin traditionally and most used for marine laminates is polyester, usually in the isophthalic form. This is because of two principal reasons: price, and ease of handling and use. Epoxy resins have been used for most aircraft and aerospace applications in several elevated temperature cure formulations, and with high strength reinforcements. It is usually in pre-impregnated form, and cured under pressure (vaccuum) at temperatures up to 175° F. Room temperature cure epoxies have also been used for boat building, usually with wood or high strength synthetic fiber reinforcement, but usually only for custom applications, because of the cost. More recently, new matrix resins have

been developed which are comprised of oligomers of standard functionality, terminated by vinyl groups. The best known of these are the vinyl esters, which are just now being tested in laminate form by the Navy and others. These resin system possess properties midway between polyesters and epoxies, but are priced only slightly above the polyesters. Another recent development is the addition of toughening compounds, usually in the form of synthetic rubber polymers, to the standard polyesters, resulting in a matrix with characteristics similar to the vinyl esters. This approach is being used by the Italian Navy in their new minesweepers, and is also undergoing tests in this country.

3.1.2.1 U.S. Navy State-of-the-Art Resins. The State-of-the-Art (SOTA) resins currently used by the U.S. Navy are polyester resins conforming to the requirements contained in either MIL-R-7575,[3-1] or MIL-R-21607[3-2] depending on the use. In addition, the MIL-R-7575 resins can be blended with up to 12% of a second polyester resin which dogs not conform to this specification, if the end application is as a matrix for glass reinforced composites.[3-3] The glass reinforcement used is E Glass, available either as woven cloth to MIL-C-9084[3-4] random mat to MIL-M-43248,[3-5] or woven roving to MIL-C-19663.[3-6] Boats built for the Navy with these materials have been limited to smaller sizes (about 60 ft), and construction has been by standard hand layup.

Resins systems which meet the requirements of MIL-R-7575 generally consist of esters based on isophthalic acid or mixtures of isophthalic and terephthalic acids. Less expensive orthophthalic acid based polyesters do not provide the weathering resistance required. There are a number of companies which manufacture polyester resins which are either on the QPL for this specification or "can meet the requirements" according to their manufacturers. The other specification, MIL-R-21607 is more restrictive.

In order to be transparent for visual inspection and still meet the fire retardancy criteria of the specification, the retardant must be part of the basic resin. Those resins that meet this criteria are therefore halogenated (chlorinated or brominated) isophthalic and isophthalic/terephthalic acid based esters.

3.1.2.2 Other Navy Resin Systems. Work on fiberglass reinforced polyester minesweepers and other large displacement ships has been underway for some time in various European countries as well as in the Soviet Union. The exact composition of the resins used has generally not been published in the open literature. An exception is the British, who have used a room-temperature curing isophthalic acid based polyester. The Italians are using a formulation known as Savid Neokil 288/T/IE. This apparently is also an isophthalic or isophthalic/terephthalic acid based polyester with vinyl terminated elastomers added to improved toughness. The monocoque hull design of the Italian ship is closest in form to the filament wound hull as envisioned for the 30 ft model. It has been reported that rubber modified isophthalic polyesters have about the same toughness as unmodified vinyl esters.[3-7]

3.1.2.3 Prior Work by LMSC and McClean-Anderson. Previous Navy contracts with Lockheed which have resulted in composite hardware bear little similarity to wet filament winding a ship's hull with a room temperature cure resin. The outer skin of the DSRV rescue submersible was built using a (then) standard anhydride cured epoxy resin. An autoclave cure of 100 psi and 375° F was required to achieve the desired properties. A submarine mast was recently built using graphite reinforcement and an amine-cured epoxy resin matrix in matched die molds at 350° F. The LMSC project closest to the subject concept is the winding of the Trident C-4 motor cases. This task, carried out by a subcontractor (Hercules) uses Kevlar reinforcement and HBRF-55A epoxy resin. The resin is "hot" for an epoxide used as a composite

matrix, and will gel at room temperature within 24 hours. If it were decided that an epoxy resin should be considered, the HBRF-55A formulation would be the starting point for the development of such a system.

The resin system used by McClean-Anderson for 3 in. thick filament wound vehicle springs was Freeman Stypol 40-2508. This is a polyester based on isophthalic acid cut with styrene monomer.[3-8] The gel time was shortened considerably by splitting the resin into two equal portions, catalyzing one portion with 2.5% MEKP and the other portion with 0.6 phr 6% Conap and 0.6 phr dimethylaniline. Each part, alone, has a gel time of approximately six hours. However, when E Glass fibers are wound through each catalyzed pot and brought together on the mandrel (2-pot filament winding), the gel time was three minutes. The rapid gelling formulation was used at the start of the winding so as to initiate exotherm and cure before the part was so thick that the heat of reaction was generated faster than it could be carried away. Once the initial exotherm had begun, the resins were replaced with a slower curing formulation, since the temperature of the part was sufficiently elevated, and it was not desired to have one layer cure prior to the application of the next. It is this relative ease of tailoring gel times and cure exotherm rates which give polyesters, and those resins which cure in the same manner, a distinct advantage over epoxy resins for this project. It should be noted that the postcure temperature for this thick part, 120° F, can be achieved quite easily with heat lamps.

3.1.2.4 Alternate Resin Systems. Besides epoxy and polyester, another class of commercially available resins can be considered candidate materials for the filament winding of a 30 ft ship model. These are the vinyl ester resins which are manufactured in this country by at least four chemical companies.[3-9] These systems, as mentioned above, have prices and mechanical proper-

ties between those of normal polyester resins and epoxy resins. Like the polyesters, they possess relatively short gel times which can be changed greatly by varying the type and amounts of catalysts and promoters used. Halogenated vinyl esters have recently been investigated by the Navy for fire retardent properties.(3-10) Recently Dow Chemical has released a rubber-modified vinyl ester resin which has an impact resistance an order of magnitude greater than some polyesters. This was accomplished, however, at a cost: reduced hardness and reduced heat-distortion temperature of the neat resin.

Vinyl urethane resins are another class of resins similar to the vinyl esters. Ashland Chemical markets a vinyl hydroxide, which the customer then formulates with the appropriate isocyanate to form something akin to an epoxy B-stage. Final cure comes with the crosslinking of the vinyl groups. Advantages of the system include reduced shrinkage (compared to polyesters) and toughness equivalent to epoxy resins. Disadvantages are moisture uptake (equivalent to epoxy resins) and lack of a good data base. As the initial reaction to form the polyurethane is practically instantaneous, the use of a system such as this may possess unique advantages in filament winding a ships hull, in terms of maintaining the fiberbands in position and controlling the progressive cure of a large hull.

3.2 SELECTED MATERIALS

Selecting materials on the basis of a paper study alone is difficult, particularly since all the relevant data are not available. However, by considering cost and availability as well as material properties, the available reinforcements and resins can be pared down to a few choices.

3.2.1 Reinforcements

The properties considered important to the selection of reinforcements for a filament wound ship and/or model hull include strength, stiffness or modulus, toughness (in terms of strain to failure and impact resistance in a laminate), moisture resistance, electromagnetic signature properties (for a minesweeper), cost, available data base, and compatability with filament winding and the selected resin system. Based on a review of the available data, and discussions with several of the material manufacturers, ratings were made on each of the subject reinforcements relative to the characteristics outlined above. The results of this evaluation are shown in Table 3-4, and from the ratings it is clear that E Glass should be the reinforcement of choice for the model hull. Due to the small cost difference, S-2 Glass should be evaluated further in terms of testing and structural calculations, before making a final selection for a ship hull. Although Kevlar has nearly equivalent tensile strength, a somewhat higher modulus, and good impact fatigue and wear characteristics, its poor compressive and shear strengths, high cost, and moisture uptake preclude it from consideration as the major reinforcement. Its abrasion and fatigue resistance might indicate its use in certain areas of a ship hull, such as decks, anchor wear areas, railings, and the like, and it should be considered for use as a coating or surface material for such areas. It is also, of course, currently being used as an armor composite reinforcement, and could have application for that purpose, even in the hull winding. The impact resistance of filament windings incorporating minority percentages of Kevlar should also be investigated.

Carbon fiber, due to its high cost, is not a contender as a hull reinforcement, but should be considered as a possible minority constituent for purposes of increasing laminate stiffness in areas where buckling is the limiting design factor. As mentioned

Table 3-4

COMPARISON OF REINFORCEMENT CHARACTERISTICS

	'E' Class	'S' Glass	Kevlar	Carbon Fiber
Strength - Tensile	Good	Good	Very Good	Good-Excellent
Strength - Comp.	Good	Good	Poor	Very Good
Strength - Shear	Good	Good	Poor	Very Good
Strain to Failure	Good	Good	Fair	Poor-Good
Impact Resistance	Fair	Fair	Good	Poor
Modulus	Good	Good	Very Good	Excellent
Moisture Resistance	Good	Poor	Poor	Very Good
Elec/Magnetic Properties	Excellent	Excellent	Excellent	Fair/Poor
Filament Winding Compatibility	Good	Good	Good	Good
Resin. Compatibility	Good	Fair/Good	Fair	Good
Cost	Good	Fair	Poor	Very Poor
Data Base	Good	Excellent	Fair/Good	Good

above, the mechanical and electromagnetic characteristics of such a mixture should be established.

3.2.2 Resins and Cure Systems

A matrix resin for filament winding with E Glass must possess several properties, including suitable viscosity and cure characteristics for filament winding, adequate mechanical properties including strength and toughness, moisture and weathering resistance, reasonable cost, and by means of additives or coatings if necessary, adequate fire resistance. Table 3-5 shows a summary evaluation of these characteristics based on information gathered from a wide variety of sources, including Koppers, Dow, Owens/Corning, Ashland, Shell, ICI/USA, NAVSEA Norfolk, DTNSRDC,(3-11&12) and the open literature on composites in the marine, aircraft, and aerospace industries.

3.2.2.1 Epoxy Resins. Several conclusions can be reached from this evaluation. Epoxy resins can provide the desired mechanical properties and weatherability, but they are not suitable for winding a large object such as a ship hull, due to their high cost, difficulty and toxicity in handling, insensitivity toward type and amount of catalyst for achieving adequate control of the curing cycle, requirements for heat and pressure to achieve an adequate cure (with the exception of some non-MIL-SPEC qualified room temperature wood laminating resins).

3.2.2.2 Polyester and Vinyl Ester Resins. The vinyl ester and polyester resin systems show promise due to their increased toughness and strain-to-failure compared to polyester, in a glass laminate, as do the rubber toughened polyesters. This last characteristic of increased strain-to-failure would allow the glass reinforcement to achieve its full strength, unlike the more brittle polyesters. The small amount of data available indicates

Table 3-5

COMPARISON OF RESIN CHARACTERISTICS

	Ortho. Poly.	Iso. Poly.	Vinyl Ester	Epoxy
Strength	Good	Good	Very Good	Very Good
Toughness/Impact	Good	Good/Very Good*	Very Good	Very Good
Modulus	Good	Good/Poor*	Good/Poor*	Very Good
Moisture Resistance	Poor	Good	Good	Good
Weathering Resistance	Poor	Good	Not Established	Good to Fair
Filament Winding Compatibility	Good	Good	Good	Fair**
Reinforcement Compatibility	Good	Good	Good	Very Good
Fire Retardance	Good*	Good*	Not Established	Good
Cost	Very Good	Very Good	Good	Poor
Data Base	Fair	Very Good	Fair	Excellent

*With additives

**Cure cycle control, room temperature cure

that the vinyl esters do not absorb water to the extent of the epoxies, but little data is available as to their weatherability and compatability with fire resistant additives.

The isophthalic polyester resins, particularly those meeting MIL-R-7575, would appear to be the baseline for use in winding a 30 foot ship hull model. It is very possible, as indicated by recent tests done for DTNSRDC,(3-11&12) that the rubber modified polyesters or vinyl esters will prove to be superior resins for ship construction. It is, therefore, a matter of defining the exact objectives of a 30 foot model phase of the program, and then seeing if the current MIL-SPEC polyester or one of the more promising new resins discussed above should used in winding the model. Another consideration is the customization of the cure system for a thick hull winding; the larger data base for current polyesters would probably make development of the cure cycle less difficult. On the other hand, if the newer resins are expected to be the ones of choice for a ship hull, then it may be better to invest the time and money in developing suitable winding cure cycles for them.

3.2.2.3 Fire Retardance. As noted previously, the MIL-R-21607 polyester resins achieve their fire retardant properties through the addition of chlorine or bromine to the resin constituents. This results in a laminate with the desired fire retardant properties, but with the disadvantages of reduced weathering and wet strength retention, particularly over time, and the production of deadly halogen gases when exposed to combustion.

One of the expected advantages of filament winding a ship hull is the higher reinforcement percentages normally achieved in filament winding compared to hand layup. While mat and roving hulls achieve 30 to 40 percent glass by weight, all roving hulls (such as the British minesweepers) close to 50% glass, and all cloth

laminates about the same (with hand layup), filament wound glass laminates routinely achieve 60 to 80% glass proportions. One result of this is a very fire retardant surface characteristic, where, when the small amount of exposed resin is burned, a glass rich char is left which insulates the substrate from further combustion. It is not known what glass percentage can be obtained on a filament wound ship hull, and therefore what degree of fire retardance will be achieved by the base laminate.

For this reason, it is proposed that the 30 foot model be wound using a non-fire retardent resin, and the question of additives or fire-retardant coatings be addressed after this baseline is established. Otherwise it will not be known what degree of fire retardance has been achieved by tke base winding before the inclusion of halogenated additives. It is for these reasons that MIL-R-7575 has been cited in the selected materials documents, as opposed to MIL-R-21607.

3.2.2.4 Summary. The selected materials, and the principal advantages leading to their selection, are shown in Table 3-6. More details on their specific requirements is given in the following section.

3.3 PROPOSED MATERIAL REQUIREMENTS

As a result of the work outlined in the previous two sections, documents were prepared to describe the selected materials in sufficient detail to allow their procurement for a model construction program.

3.3.1 Material Requirements Documents

The first document is a "Proposed Material Requirements" summary which lists the selected materials and applicable specifications.

Table 3-6

SELECTED MATERIALS

Application	Material	Advantages
REINFORCEMENTS		
- Winding Roving	- 'E' Glass MIL-R-60346	- Low cost, resin compabible
- Winding Additives (Optional)	- Kevlar AMS-3901	- Added toughness
	- Carbon fiber AMS-3892	- Increased modulus
- Surfacing Reinforcement	- 'E' Glass MIL-C-9084	- Low cost, resin compatibility
	- Kevlar cloth AMS-3902	- Toughness, impact resistance
RESINS		
- Baseline	- Iso. Polyester LMS Spec. (MIL-R-7575 BASED)	- Cost, cure, moisture resistance, F. W. compatibility, data
- Alternate	- Toughened Polyester	- Improved impact resistance and strain
	Mod. LMS Spec.	
	- Vinyl Ester	- Improved impact resistance and strain
	Savid 288T equiv.	

It is included as Appendix B-1 to this report, and covers glass roving and cloth, Kevlar roving and cloth, and the matrix resin. In the case of the resin, it refers in turn to a "Proposed Requirements for Resin, Filament Winding, Room Temperature Curing" document, which is included as Appendix B-2 to this report. Although this document is refered to as a "proposed requirement" instead of a specification, it is in the general form of a specification, and could be turned into such by finalizing the recommended values of certain variables such as minimum test results. Since it is recommended that this be done only after evaluating the results of preliminary testing in the next phase of the program, the document is considered provisional and was thus titled a "proposed requirement" instead of a "specification".

The resin document covers both isophthalic polyester and vinyl ester resins, since a final determination of the selection between those two candidates has not been made, as discussed in the previous section. The requirements document covers included specifications, material characteristics and properties, glass reinforced test panel properties, test methods, quality assurance provisions, and applicable examinations and tests.

Along with the Process Requirements document discussed below, and the Winding Procedure summary in Section 4.3, this document provides the information necessary to begin the model fabrication phase of the Filament Wound Ship Hull Program.

3.3.2 Process Requirements Document

In addition to the specifications and Requirements Document for the resin, a document was prepared outlining the "Proposed Process Requirements for Wet, Two-pot, Filament Winding of a Primarily E-Glass Roving Reinforced 30 Foot Ship Hull". As in the case of the resin, this document is considered preliminary and subject

to revision as the model phase progresses, and was thus titled a requirement instead of a specification. It is primarily intended to indicate the form and content of such a process specification, and therefore contains information on such items as the winding machine, mandrel, instrumentation, winding procedures, cure, and finishing which may or may not apply to the 30 foot model as finally developed. In this sense it is not intended to be restrictive, but rather an aid in developing a final process specification document for the winding of the model, along with a revised winding plan and procedure as shown in Section 4.3. This Process Requirements document is included as Appendix B-3 to this report.

3.4 REQUIRED MATERIALS DEVELOPMENT

As a result of the materials investigation discussed in the previous sections, it is apparent that there is a significant amount of development effort required with regard to reinforcements, resin systems, and the fabrication process for a filament wound ship hull, before the state-of-the-art in this area will support the construction of a large filament wound ship hull. It should be noted that not all of these requirements are necessary prerequisites to the winding of a model hull, although those that involve the application and cure of the resin system must at least have an adequate solution before a model hull can be successfully wound.

3.4.1 Reinforcement Materials

There are several areas of reinforcement technology that should be extended or at least evaluated before undertaking the winding of a ship's hull. These will be discussed in the following paragraphs, and where applicable it will be noted if it is recommended that any related effort be made in each area during the

model winding phase of the program.

3.4.1.1 Heavier Reinforcement Rovings. The bulk of reinforcement wovings used in boat and ship hulls up to this time are the woven roving fabrics identified as 24 oz, indicating a fabric weight of 24 ounces per square yard. Each layer of this material, when combined into a hand layup laminate, results in a thickness of about 0.038 in. per layer at 50% glass by weight in an all roving laminate.(2-7) Based on the structural analysis previously described, and the design of the monocoque Italian minesweeper hull, total hull thickness may be up to a maximum of 4 to 6 inches in a GRP minesweeper. For a 4 inch thickness, this would require 105 layers of 24 oz. roving or its equivalent in filament winding.

In the case of the Italian ships, a heavier roving fabric was developed with a weight of about 44 oz./yard. If the thickness is assumed proportional to weight, this would yield a thickness of .070 in./layer, or 57 layers in 4 in. thickness. In a hand layup hull this represents almost a 50% savings in shell laminating manhours, and is a very important cost reduction item. (The assumption of constant manhours per layer may not be absolutely correct, due to possible increased rollout and compaction time for the heavier layers.) In a filament wound hull, it was estimated in Section 2 that the roving size for a ship could be the maximum available, 113 yield (yards/pound) roving, or because of the difficulty of handling this weight, 225 yield, which is commonly used in winding. Depending on the winding settings and techniques, the 113 yield roving at a band density of 7 rovings/inch would result in a thickness of about 0.090 in. at 60% glass, and for the 225 yield roving a thickness of 0.045 in. would be obtained for the same 7 rovings/inch and 60%. Thus, the heavier roving would allow winding a 4 in. hull thickness with 44 layers, whereas the 225 yield would require 89 layers. Although

the manpower considerations are not as great as in the case of hand layup, it is still desireable to simplify the production process by limiting the number of plies.

It is, therefore, recommended that the use of the heavier rovings be investigated, and suitable testing undertaken to identify the problems in material handling and machine configuration which would be required to successfully utilize the heavier rovings in the projected bandwidth of about 24 inches.

Since it is intended that the model be wound at scale layer thickness, a roving weight of 450 to 900 will be used, depending on whether it is desired to scale the 113 or 225 yield material. Thus it is not necessary to accomplish this development effort before winding the 1/5 scale model.

3.4.1.2 Mixed Reinforcements. As previously discussed in Section 3.1.1, the major application foreseen for Kevlar or carbon fiber in a ship hull winding would be the inclusion of small percentages (up to 10-20%) of these higher strength or stiffness materials. The objective would be to increase the impact and abrasion resistance of the laminate (in the case of Kevlar), or the strength and stiffness of the laminate (in the case of carbon). These fibers could be distributed evenly throughout the laminate, concentrated near the surface to resist wear or bending stresses, or distributed through the thickness in a proportion related to bending stress, forming a quasi-structural sandwich. As a result of the previous testing done on similar hand layup samples, it is known that this technique can result in increased material properties. To accurately define the character and quality fo such increase, however, samples must be wound in a controlled manner, and testing in accordance with accepted standards.

It is suggested that the following three kinds of samples be fabricated and tested against an all glass reference:

(1) Kevlar included in the surface layers as 100%, 50%, and 25% of the layers in the outer 25% of the sample thickness (samples to be at least 1 in. thick). Test for bending strength and stiffness and impact strength.

(2) Kevlar included throughout the thickness as 10% and 20% of the fiber content. May be included in each fiber bundle as a portion of the fibers, or as separate bundles; method to be determined. Test for tensile, compression, and bending strength, as well as short beam and interlaminar shear.

(3) Carbon fiber, included as 5, 10, and 20% of the fiber content throughout the thickness. Same tests as (2), plus applicable electromagnetic tests to provide signature data.

It should be noted that these tests could be performed on samples wound on a special mandrel, and then cut into test samples, or the various winding procedures could be utilized on specific areas of the model hull, and samples later cut from these areas. There is little doubt that more consistant and reliable samples may be obtained from special samples, but it is not necessary to the success of the model hull that these tests be accomplished before model fabrication. It is suggested, however, that before including mixed fibers in a model hull matrix, that at least some testing to provide assurance that the concept is worth pursuing would be desirable.

3.4.1.3 Improved Glass Rovings. Before designing and fabricating a filament wound ship hull, the performance and cost effectiveness of the relatively low cost S-2 Glass fibers should be established. This need not be accomplished before winding a model

hull, but as suggested in the following section on resins, if it appears that there is a high likelihood that the S-2 Glass would be used in a ship hull, then it would be prudent to do at least some testing to establish its characteristics in a filament wound laminate before selecting the material for the model. It is therefore suggested that simple flat sided cylindrical samples of E & S-2 Glass in the selected resin be tested as follows:

(1) S-2 Glass rovings throughout the laminate sample, for comparison with baseline E Glass samples.

(2) E-Glass control samples, to provide base data on all material characteristics, including stiffness and strength, impact, percent glass by weight, fire retardance, and moisture resistance.

3.4.2 Resin Systems and Cure Cycles.

As in the case of reinforcements, there are several developments in resin materials which suggest that the resin selected for winding a ship hull might be other than the current MIL-R-7575 or MIL-R-21607. The primary candidates would seem to be a toughened isophthalic polyester, or one of the previously discussed vinyl esters. The major point in reference to these materials relates to development of a special cure cycle for filament winding of a ship hull.

If effort is to be expended in developing these production techniques, it makes economic sense to develop them for a resin system projected for a full scale hull. Otherwise, progress made in developing a modified cure cycle for the current resins would have to be repeated for any new resin adopted. In the case of the rubber toughened resins, composition changes are not apt to severely effect the cure cycle, but in the case of the vinyl esters, the differences could be greater even though the curing agents might be the same. As previously discussed, the cure

cycle of the vinyl urethanes includes an initial reaction to form the urethane which is similar to an epoxy B-stage, and would be quite different from the polyester and vinyl ester cure, although it might provide a good method for B-staging a filament wound laminate.

Due to the cost and cure cycle times involved, the development of these cure cycles and resin systems should be performed on small filament wound samples having significant thickness, and fiber laydown rates similar to the full size hull. The best approach to this development would be the fabrication of small flat sided cylinders, perhaps 12 in. x 6 in. x 3 ft long, with thickness up to 1 in.

Because the techniques are required for winding the model as well as the ship, these tests, and mechanical testing of the resultant windings, should be given the highest priority in the overall program.

3.4.2.1 Primary Resin Systems. It is proposed that samples of the resins of interest be obtained, as well as samples of MIL-SPEC polyester resins, and test pieces of all of the above be wound to investigate the tailoring of the cure cycle. On those systems which appear to be most promising for a full scale winding, structural test samples should then be wound to allow determination of physical and mechanical characteristics.

Based on the results of current Navy test programs, it would appear that both vinyl ester and rubber modified isophthalic polyester resins should be tested, both with and without fire retardant additives.

3.4.2.2 Secondary Bond Resins. To allow development of adequate bulkhead and deck connections, current secondary bonding resins

systems for use with cured polyester or vinyl ester resins (depending on the matrix resin selected) should be reviewed, and the most promising candidates selected for testing in a simulated joint. In past programs, statements have been made to the effect that since epoxies generally require heat and pressure to achieve their full strength, there is no point in choosing them over polyesters for cold unclamped secondary bonds in a polyester structure. Since there is quite a bit of data to indicate that various room temperature cure epoxies have higher peel and shear strength than polyesters, it would appear that the question to be answered is what is the performance of these adhesives compared to the parent polyester resin, when used as a secondary bonding agent. Test results can be cited to support the use of both systems when bonding polyester structures, and the introduction of vinyl esters with much higher available strains (up to 9%) complicates the question further.

It is therefore recommended that a survey be made of available bonding systems and performance data, and several of the most promising be selected for testing. The test articles and configurations should be selected to simulate as closely as possible the kind of joints being considered for the hull/deck, hull/bulkhead, and bow and transom joints, since the type of loading and auxiliary fastening will strongly effect the outcome of the tests. A large amount of similar work has been accomplished by the British in the WILTON program,[2-7] and will provide a good starting point for such an effort.

It is of course not necessary to perform this work before building a 30 ft model, but if there is any chance of testing the model in a manner which would involve these joints, the developement work should be accomplished before the model joints are designed and built.

3.4.3 Laminate Testing.

In order to provide information necessary to design the winding patterns for a full scale hull, it will be necessary to have sufficient knowledge of the performance of laminates with different fiber orientations with respect to the principal design stresses. As mentioned in Section 2.0, this will require a more thorough knowledge of ship loading and stress distribution, but it will also require a knowledge of the performance of laminates with different fiber orientations in the different layers. Existing analytical tools, such as Lockheed's "ADVLAM" code, allow predictions of stress in each laminate layer as a result of overall laminate stress. The interlaminar shear strengths and performance cannot, however, be predicted at this time, and so tests and analyses must be performed on projected laminate configurations to establish failure modes, and to correlate performance and predictions. Since this is not a simple or inexpensive effort, it would not be reasonable to attempt to perform it before building the 30 foot model, and it is not necessary to the model demonstration of the filament wound hull production process.

It is emphasized that tests and development efforts such as those discussed above that have determined the overall timetable necessary for the design and fabrication of the existing GRP ships. These efforts therefore must be started and accomplished in a timely manner to prevent them from becoming more critical than the actual winding process and machinery development in determining an overall program schedule.

It is recommended that at the beginning of the next program phase a planning effort be started to scope, estimate, and schedule the various laminate analysis and testing tasks. These results, along with similar estimates of the other necessary development

efforts, should then be integrated into an overall program plan to allow for adequate funding, facilities planning, and manpower planning for the projected program.

3.4.4 Design Details

This section will discuss necessary development effort in the design of joints, edge treatments, and surface finishes.

3.4.4.1 Joint Design Details. As mentioned in Section 3.4.2.2 on bonding resins, joint design details will be critical to the development of a successful filament wound ship hull. If the model hull is likely to be subjected to any testing, it will be prudent to make sure that the preliminary joint designs used in it have adequate performance to at allow successful testing of the basic hull and deck structure. If the shell loadings cannot be transmitted to the bulkheads and decks in a realistic and satisfactory manner, the test results will be unsatisfactory.

It is therefore recommended that detailed joint designs for the major hull, deck, bulkhead, and transom joints be started at the beginning of the next phase of the program, and the preliminary study results be incorporated in the 30 foot model joint designs. Since these involve the detailed configuration of the mandrel in the case of the bulkheads and decks, the two design efforts should run concurrently.

3.4.4.2 Edge Treatments. Another area of design which will have to be addressed with sample fabrication and testing is the method of finishing cut edges of the filament wound laminate. Since experience has shown that exposure of cut ends of the glass reinforcements will wick water into the resin/glass interface and degrade the bond, it is necessary to seal these cut edges with a reinforced resin coating. Since these are secondary bonds, the

selection of adequate materials and methods for application is important to the control of labor costs during outfitting. The technology is basically no different from that in normal SOTA GRP hulls, and so current techniques should be reviewed and the most promising selected for testing and evaluation before constructing the full size hull. Only a small portion of this effort needs to be accomplished before winding the model hull, in order to demonstrate adequate preliminary techniques that will provide assurance that this design problem can be successfully solved for a full scale hull.

3.4.4.3 Surface Finish. Because the surface of a filament wound hull will not be as smooth as that of a contact female molded hull, some smoothing of the surface will probably be required. Since the model hull will provide the first indication of the actual magnetude of this problem, it will provide an opportunity to try, *in various areas of* the hull, different methods of achieving adequate fairness and smoothness. It is probable that the two requirements for a smoother than wound finish wil be (1) the hydrodynamic drag of the hull, and (2) the walking surface requirements on deck. The hydrodynamic fairness requirements may be the more stringent of these, although in a 10-15 knot hull even these should not be extremely critical. The major consideration will be to avoid a fuel utilization penalty when compared to a contact molded hull under normal operating conditions.

It is proposed that the application of fairing compounds, possibly fiber reinforced and/or toughened to resist UNDEX and local impact deflections, be tried on the model hull. If necessary, the hull should be prepared of by the grinding down of high spots. In a later phase of the ship program, fairing compounds and/or bottom paints could be applied to filament wound test cylinders and tested for impact and deflection damage resistance.

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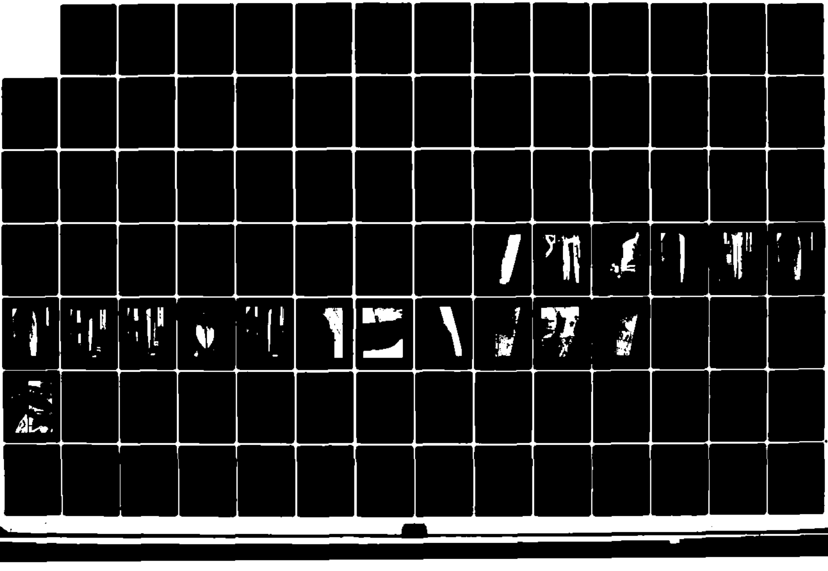

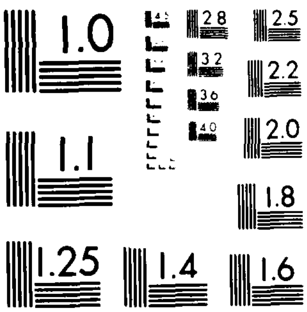

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963-A

3.4.4.4 Laminate Repair. Because all ship hulls sustain minor damage which must be repaired, and some sustain major structural damage, methods and procedures to accomplish satisfactory repairs must be developed. U.S. and other Navies currently have procedures in hand for repair of hand layup hulls, and these would form the basis for developing techniques for filament wound hulls.

One major difference, however, may be the higher glass content of a filament wound hull. Current Navy boats have glass contents of 30-40% by weight, due to the use of mat and woven roving. The British minesweepers achieve closer to 50% glass, by the use of an all woven roving laminate and close quality control. A filament wound hull may approach 60-70% glass content, however, and the challenge will be to hand fabricate repairs that can achieve the strength of the parent laminate. Probable techniques will include the use of unidirectional reinforcements, special resins, possibly pressure bags to provide compaction, and if necessary additional thickness to compensate for lower laminate mechanical characteristics.

Before getting too far along in a ship development program, these techniques should be developed and demonstrated to assure the viability of a filament wound hull in actual fleet service. Thus this effort should be included in the previously described planning effort, to be accomplished in the next phase.

REFERENCES - SECTION 3

NUMBER TITLE

3-1 Specification MIL-R-7575, "Resin, Polyester, Low Pressure Laminating".

3-2 Specification MIL-R-21607, "Resin, Polyester, Low Pressure Laminating, Fire-Retardant".

3-3 Specification MIL-P-17549, "Plastic Laminates, Fibrous Glass Reinforced, Marine Structural".

3-4 Specification MIL-C-9084, "Cloth, Glass, Finished, For Resin Laminates".

3-5 Specification MIL-M-43248, "Mats, Reinforcing Glass Fiber".

3-6 Specification MIL-R-60346, "Roving, Glass, Fibrous (For Prepreg Tape and Roving, Filament Winding, and Pultrusion Applications)".

3-7 "Rubber Toughening of Polyesters: The Effect of Isophthalic Acid Content", C. S. Nichols & G. J. Horning, Paper
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3-9 "Vinyl Ester Resins", M. B. Launikitis, Chapter 2, Handbook of Composites, G. Lubin Ed., Van Nostrand, Reinhold, New York, N.Y., 1982.

3-10 "Investigation of Kevlar and Glass Reinforced Plastic Materials for U.S. Navy Small Craft Structural Applications", E. L. Lash, NAVSEADET Norfolk, Report No. 6660-79, March 1981.

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SECTION 4
FILAMENT WINDING ANALYSIS & DESIGN

This section will review the current state-of-the-art (SOTA) in filament winding versus the technology required to wind a shape like a ship hull, the winding experiments that were carried out as part of this contract, the winding problem areas indicated by the results of these experiments, and the selected winding configuration or design for the 30 foot model hull. It will also review the preliminary design of a mandrel suitable for winding the model hull, the modifications to current filament winding equipment necessary to allow winding of the model, the work accomplished to date in investigating the use of CAD/CAM to develope winding paths in the computer instead of on the mandrel, and the full scale problems that are anticipated to occur in the winding of a full scale ship hull but not necessarily in the winding of the 1/5 scale model.

4.1 CURRENT FILAMENT WINDING STATE-OF-THE-ART

As was pointed out in the Lockheed proposal for this study, the filament winding industry and manufacturing science has already moved beyond the simple cylindrical shapes with which it started, and has demonstrated the ability to wind larger and more complex shapes, to use more advanced fibers and resins than those it traditionally used, and to develop new techniques and machines as the complexity of the product increased.

Some examples of this expanding technology are the large missile motor cases currently being produced with both S Glass and Kevlar in epoxy resins, the railroad hopper car of non-circular design produced for Southern Pacific (called the "Glasshopper"), the

complex self-framed isogrid structures currently being developed for Navy structural applications such as helicopter platforms, large (11 ft dia. by 60 ft long) fiberglass pipe sections, vehicle springs up to 1-1/4 in. thick, and firemen's oxygen tanks wound over a core/mandrel of thin aluminum sheet. Many of the techniques developed for these products are applicable to the winding of a ship hull, but as was demonstrated in the winding of the 4 foot ship model by McClean-Anderson in the previous phase of this program, the shape of a ship hull provides some new problems that had been avoided in the previous applications.

These differences will be discussed in the following sections. Most of them are due to the unique and irregular shape of a ship hull, but some of them derive from the size and weight of a 150 to 200 foot ship hull and the structural mandrel necessary to support it during manufacture.

4.1.1 Major Differences in Winding a Ship Hull

The following sections will describe briefly the principal items which make the winding of a ship hull unique, and the proposed solutions to these problems will be discussed in later sections of the report.

4.1.1.1 Fiberband Slippage. One of the major differences between the shape of a ship hull and normal filament wound (FW) shapes is the sharp discontinuity at the deck edge, and the way that edge tapers inward toward the bow. The result is that the fiber bands that pass over the deck edge are stable in their position only for certain angles of the fibers with the ship axis. For all other angles, there is a tendency for the tension in the fibers to pull the bands lengthwise along the hull, displacing them from their desired position. This band slippage must be prevented if all of the desired fiber path angles are to be achieved, since

the stable fiber paths cover only a small portion of the desired range of orientation angles. Another area where this slippage occurs is the stem or bow edge, and if the transom is wound integrally into the hull, the transom edges would also be problem areas for slippage. In the case of a minesweeper, the break in deck level at the foreward end of the aft working deck presents edges which may be slippage areas, depending on the desired orientation of the fibers.

4.1.1.2 Edge Compaction of FW Laminates. A related problem which occurs when FW fiberbands are turned around a sharp corner such as the deck edge is the compaction of the fiber bands. The winding tension in the bands cause a force normal to the edge radius as the band passes around the corner, and results in a compacting force normal to the plane of the laminate. This force squeezes the resin out of the matrix, resulting in a thinner and resin poor area with reduced strength compared to the basic laminate.

4.1.1.3 Complex Stress Distributions. Most products built by filament winding in the past were cylinders and quasi-cylinders which had their major loading in either the longitudinal or hoop direction, usually because of internal pressure. Therefore, most of the fibers were placed in a direction which would reduce the hoop stress. The structural efficiency of the FW was high because this is the direction of the greatest strength of the laminate.

In a ship hull, the traditional major design stress is a longitudinal bending stress due to the action of the waves in supporting only a portion of the hull. There are other local loads such as hydrostatic pressure and docking, and other point loads such as weights on deck. There are also secondary stress distributions due to internal structure such as bulkheads, intermediate decks, and machinery foundations. In a minesweeper, UNDEX loads cause panel bending and possibly hull whipping (dynamic bending). The

result of all of this complex loading is that the stresses in a ship hull are complex, dynamic, to a great extent unknown in an exact local sense, and subject to change over time. Thus, it follows that the identification of loads, resultant principal stresses, and combined or superimposed stresses is a much more complex problem than a pressure vessel, and the selection of fiber paths in each layer, the proper combination of layers, and the required reinforcements for increased local loads are all subjects which complicate the design of a ship hull compared to most regularly shaped and loaded filament wound products.

4.1.1.4 Shape limitations on Winding Patterns. A related limitation in the winding of a ship hull shape is that the normal FW techniques (i.e. choosing a stable fiber path and then repeating it down the length of the object and back in the opposite direction) cannot be accomplished on a ship hull because the shape constantly changes over the length. As will be discussed in the section on winding experiments, this is particularly true in the ends of a ship due to hull taper, while the more cylindrical midships section is not too different from normal FW shapes. Also the slippage problems discussed above tend to limit the winding angles which can be used in a particular area, especially in the ends of the ship.

4.1.1.5 Fiberband Bridging. For reasons of seaworthiness, ship hulls often contain areas of reverse curvature or hollows, such as flare in the topsides forward or sheer in the deck viewed from the side. Since fibers under tension tend to stay in a straight line, there is a tendency for FW fiber bundles to "bridge" or rise off of the surface of the mandrel in such areas. Since the areas are sometimes only hollow in one direction, not all fiber paths in a given area will bridge, and in fact the fibers in the flat or convex direction can even act to restrain the bridging fibers in the concave direction.

4.1.1.6 Turnaround Areas. One of the techniques that has been developed in conventional filament winding is the ability to turn fibers around at the end of the part and wind them back the other way, in a desired path. In some cases this is done on the mandrel, as for a tank with hemispherical ends, and in other cases it is done off of the part on the mandrel shaft, or a collar fixed to that shaft. In the case of a ship hull, the difficulties of fiberband placement on the bow and transom to prevent slippage are compounded by this requirement to turn the fiber bands back onto a desired return path.

4.1.1.7 Laminate Thickness and Cure. The projected laminate thickness of up to 6 inches in a 150 foot ship brings up another problem related to keeping the fiberbands in place during curing; preventing excessive heat buildup during the exothermic curing of the resin system. This problem has been addressed in FW laminates up to 1 or 2 inches in thickness, but not over the large area and thickness of a ship hull. A related problem is the long elapsed time between passes of the fiberband over a particular area, and the relationship of that time to the cure cycle of the resin system.

4.1.2 Additional Winding Complexities

In addition to the challenges presented in the previous paragraphs, there are other considerations unique to the winding of a ship hull which have not before been addressed by the FW industry.

4.1.2.1 Mandrel Stiffness. When fibers are wound onto a FW mandrel, they must remain in essentially the same position until they are at least partially cured. If the matrix of fibers and resin is flexed during the curing cycle, the result will be the destruction of the structural integrity of the matrix. For the

fibers oriented along the longitudinal axis of the hull, it is extimated that the deflection of the mandrel if it is rotated must be less than 0.1% in the fiber axis, or the laminate will be damaged. This means that the mandrel has to be very stiff and rigid to prevent this deflection. This subject willl be further discussed in the section on mandrel design.

4.1.2.2 Mandrel Removal. In the case of many FW products, the mandrel is removed from the completed part by disassembly and exit through a small opening, or even by dissolving or destroying a mandrel material such as salt or plaster. In the case of a ship, particularly if the internal bulkheads or decks are installed in the mandrel and wound into the hull, the design of an adequately stiff and light but removable and reusable mandrel is a more difficult challenge.

4.1.2.3 Outfitting Access. A final problem to be addressed is the methods and cost for outfitting a FW ship after completion of the basic structure. In conventional shipbuilding, much of the machinery, piping, wiring, and outfitting is done before assembly of the hull modules or the installation of the deck and superstructure. If the hull and deck are wound as a unit, all of this equipment will have to be introduced through hatches, doors, and special construction openings such as the transom or uptake cutouts. Such limited access could result in additional construction costs and tend to offset the labor savings in the hull fabrication, which is only on the order of 20% of the ship cost (not including weapons). One possible solution would be to include much of the machinery and outfit in the mandrel with the bulkheads and decks. The primary drawback of this solution would be the increased weight of the mandrel assembly, particularly if it is to be rotated.

4.2 WINDING EXPERIMENTS & ANALYSIS

This section will review the several winding experiments which were accomplished on a 10 foot model of the MCM-1 hull, and discuss the implications of the results.

4.2.1 Model Fabrication

Early in this study, as a result of discussions with McClean-Anderson (M-A) and review of the results of their study and 4 ft model construction, it was decided that a larger model on which experimental windings could be placed would be very useful.

Using the lines of the MCM-1, since no MSH lines were yet available, a 10 foot model was constructed out of a wood core covered with high density foam. The foam was contoured to shape and then covered with an epoxy to provide a firm surface for winding. The model is shown in Fig. 4-1. As can be seen, waterlines, and later station lines, were scribed into the surface to assist in locating fiber paths and positions. (Note: Figures for Section 4 are located at the end of the section, for convenience in comparing the photographs). This model was then mounted on the Lockheed M-A filament winding machine, and the experiments begun.

4.2.2 Preliminary Hand Winding

The first experiments were conducted by hand feeding a Kevlar roving onto the slowly rotating machine by hand. The purpose of this exercise was to identify the general winding characteristics of the shape, since it was new to the FW personnel involved, and to repeat some of the experiments and fiber paths discussed by M-A based on their previous work on the 4 foot model. Some of the resultant paths can be seen in Fig. 4-2 and 4-3.

The specific observations made were of generally possible fiber paths, slippage areas and paths, bridging areas and paths, turn-around areas and characteristics, ability to vary and control fiber paths in critical areas, and optimum winding head (hand) positions. Some of the patterns were then repeated using the digital controller, to gain general experience with the input of complex paths to the machine controller.

4.2.3 Helical Winding Experiments

It was next decided to place some helical windings on the model mandrel to observe the effect of the hull shape on this common and simple type of winding, where the winding head advances along the hull at a constant ratio to the rotation speed. This of course results in a helical winding path on a cylindrical mandrel.

4.2.3.1 <u>60° Winding Experiments.</u> The machine was first set for an advance corresponding to a 60° angle of the fiber to the longitudinal hull axis in the midship or maximum girth area. The result is shown in Fig. 4-4. The rovings were spaced at about 5 inch intervals along the hull to provide coverage adequate to identify all of the problem areas, and the rate of change of the winding patterns. The relative uniformity of the winding over most of the hull, except for the turnaround area patterns in the bow, can be seen in the photograph. The pattern was then repeated in the opposite direction along the hull with the mandrel rotating in the same direction, yielding a -60° winding angle.

4.2.3.2 <u>45° Winding Experiments.</u> The machine controller was then set for plus and minus 45° winding angles, and fibers re-wound onto the blank mandrel with the results shown in Fig. 4-5. In general the results were very similar to the 60° experiments, except that the variations in fiber spacing at the ends of the

hull were more evident.

4.2.3.3 <u>30° Winding Experiments.</u> Finally, windings of plus and minus 30° were applied to the model. The results are shown in Fig. 4-6. Again it can be seen that the reduced angle has increased the tendency of the fiber path spacing to change toward the ends of the hull. The relative change of angle i also increased in those areas, such as the flat of the botto ft, where the change in girth from the midships area is the grea t.

4.2.3.4 <u>Helical Experiments Results.</u> In each of the cases the resultant winding angles were recorded at the intersection of each station and waterline and the nearest fiber. The wind angles obtained on the port side were within 5° of the basic wind angle with a 90% compliance (90% of the recorded paths were within 5°), but on the starboard side the compliance was only 55%. This difference was due to the fiber lead being different from the fixed payout eye of the machine when moving down the tapering hull and coming back. To compensate for this variation, another winding was tried starting at a point 180° around the hull from the original starting point, and with the mandrel rotating in the opposite direction. The result was a pattern nearly identical but opposite to the first pattern wound, thus demonstrating that a balanced laminate can be produced despite the non-symmetry of the hull shape fore and aft. The data from the 45 and 30 degree experiments is included as Appendix A to this report.

4.2.4 Low Angle Winding Experiments

To achieve low angle windings, bewtween 10 and 30 degrees, the use of an auxiliary non-linear machine axis was necessary. A 15° helical program was entered into the M-A winding machine controller with auxiliary axis movement in the crossfeed direction, and the corresponding program was recorded. The winding pattern,

shown in Fig. 4-7, was evaluated with mandrel rotation in both directions, and again a 3 to 5 degree difference between port and starboard sides for the same rotation was noted. For each direction and angle, reversing the rotation again balanced the patterns. The localized angle deviated more from the desired angle than was the case for the higher angles patterns due to the restricted turnaround areas at each end of the hull. The turnaround at the stern was improved by extending the hull beyond the transom position. It is recommended that this be done on the 30 foot model, or else a turnaround collar used to allow for improvement of the low winding angles in the stern. To improve the fiber paths in the bow area, an extended turnaround area is necessary. One way to improve this area of the winding would be to stop the hull winding just forward of the first or collision bulkhead, and use the area forward of this as a turnaround which could be shaped to suit and cut off of the hull molding after cure. A separate bow molding could then be wound or hand laid up, and attached just forward of the collision bulkhead with a bonded and bolted secondary joint. A corollary advantage of this approach would be that hull access for outfitting would be improved, and replacement of the bow after collision damage would be simplified.

4.2.5 Parallel Bow Winding Experiments

As an alternative approach to winding the difficult bow area, a non-linear carriage movement program was entered into the machine controller, and by using a series of small pins along the keel and deck edge, a parallel pattern, symmetrical about the keel, was wound onto the forward part of the hull without slippage or change in relative band position. The sides were wound at 45°, with the advancement of the fiber band to the next position taking place entirely on the deck. The result was a winding with local angles within 5° of the nominal 45° over most of the area,

increasing to 10° variation in the last few bands at the bow. The result of this experiment is shown in Fig. 4-9. This technique of parallel windings could be used to obtain any other winding angle, depending on structural requirements, and would yield uniform bandwidth over the entire ply. It could also be used to wind a separate bow module with any desired ply orientation. Winding two bow modules back to back would also eliminate the waste of fiber in a turnaround area which is discarded after cure.

Particularly at the lower angles, this technique is dependent on some restraint of slippage at the bow and keel, because of the abrupt change of fiber angles at those edges. The pins and other techniques to accomplish this are discussed in a succeeding section.

4.2.6 Single Direction Winding Experiments

Another technique attempted in order to achieve the desired winding patterns was a single direction helical program. The carriage was allowed to travel from the headstock (at the stern) to the tailstock (bow) as programmed, but then the fibers were secured to the mandrel and cut when the band reached the bow. The carriage was next returned (deadheaded) to the headstock without winding, the fiber band re-attached to the mandrel at the desired location, and then the machine allowed to continue as programmed. This procedure demonstrated that by eliminating the turnaround area in the bow, and winding in only one direction, a more uniform winding pattern could be maintained. By reversing the mandrel direction and following the same procedure, an identical winding pattern was achieved in the reverse (negative) direction.

4.2.7 Circumferential (90°) Winding Experiments

Circumferential winding p.-terns were accomplished with no major problems, as would be expected. They are shown in Fig. 4-10. The utilization of pins along the deck edge and keel eliminated the slippage that would have otherwise occurred in the bow area, except for the small amount of slippage between pins. In a full size ship this would have to be carefully controlled to prevent uneven buildup and resin rich areas along the deck edge. One problem that was noted was the bridging of some fibers in the area of the bow flare hollow. This problem is a function of hull shape and the fiber path. It can be eliminated by removal of the hollow from the ship lines, or by physicallly restraining the fiber bands to the mandrel or underlying ply. This could be accomplished with mechanical fasteners (fine staples) or the adhesion of a "sticky" or quick B-staging resin which sets up sufficiently to hold the fibers in place while they are still restrained by a roller or other mechanical means. These techniques will be discussed and demonstrated in a later section.

4.2.8 Axial (0°) Winding Experiments

The final patterns attempted were axial windings. A number of different techniques to achieve these 0° windings were discussed and attempted. The initial attempt was a pure axial winding pattern with pins on the bow and stern to secure the fibers in place. On the topsides, these windings were easily obtained, but on the bottom of the hull the taper in beam resulted in either gaps or overlaps, depending on the spacing of the bands. Although complete coverage could be obtained in the stern, the fibers in the midships area would show gaps due to the increased girth. As the bands moved forward they came back together again, and finally overlapped due to the still smaller girth. To overcome the gaps in the bilge area amidships (if the fiber spacing is kept

constant on the bottom), unidirectional roving fabic could be cut and laid down in the open areas. Alternatively, if sufficient strength for the bilge area could be developed with the low angle helical windings, then the axial winding could perhaps be used only on the bottom area where the bending stress and docking and UNDEX loads are higher than on the sides.

Due to limitations in the current configuration of the M-A winding machine, complete coverage with axial windings could not be attained. With certain machine and controller modifications, which will be discussed in a subsequent section, a satisfactory layer of axial windings could be achievgd.

4.3 WINDING PROBLEMS AND AREAS

In this section, the specific problem areas of fiberband slippage, bridging, sagging, uneven thickness buildup, and edge radius compaction will be discussed. Demonstrated or proposed solutions to these problems will also be covered.

4.3.1 Fiberband slippage

The first problem encountered in the helical winding experiments was slippage of the fiberbands at the keel and deck edges, especially near the bow. This slippage is inversely proportional to the angle of the fiber path with the ship axis, as noted in the preceding section. Other areas where this would be a problem are the stem, the transom edges, and the deck break discontinuities.

4.3.1.1 Proposed Solutions. As discussed in the previous M-A report, the solution to this problem is to provide mechanical restraint to prevent the sliding of the fiberbands, thus allowing the winding of any desired angle in any area of the hull. The method originally proposed by M-A was to use small steps or

ledges to remove the angle which provides the slipping force, and it has been shown that this technique is effective. On consideration of the problems of providing such steps in the appropriate directions for each fiberband in each of 50 to 100 winding layers, it was decided to examine other methods which might be as effective as the steps or ledges, but more easily applied anywhere they prove to be necessary. It would be desirable to find a method that could be used without modification of the mandrel surface, and without causing discontinuities in the structural laminate where the steps end and begin.

One possibility appears to be the use of small wire staples, of a material which would be non-corrosive and non-magnetic, such as bronze or stainless steel (CRES). Because the effect of a large number of these small wires in the deck edges and keel/stem area is not known, another possibility that suggested itself was the use of pins made of pultruded GRP, which would have the same basic material properties as the parent laminate. It is proposed that either of these methods could be accomplished by driving the staples or pins into each layer of the laminate as it is wound, as long as the underlying laminate is still in the relatively soft B-staged condition. It would also seem feasible to incorporate an automatic stapling or pinning device into the machine winding head, and include a signal for driving a staple into the band as a part of the coded machine instructions. These techniques must be experimented with manually, with both dry and wet windings, before the design of such an automatic device is undertaken.

Another possibility is the retention of the fiberbands in position by a very viscous resin, or by quickly B-staging the conventional resin system. This could be done by using a two-pot resin system which gels quickly after fibers passed through the two pots of differently catalized or accelerated resins mix together

on the mandrel. It might also be accomplished by introducing heat at the point of fiberband application with a heated roller or jet of hot air, or by using light to set off a special sensitized curing process. The highly viscous resin might be implemented by using high pressure resin injector pumps instead of a bath to saturate the fiberbands with an already viscous resin, or by designing a resin system with a quick change of viscosity as distinct from the final cross polymerization of the curing process. All of these possibilities should be examined in detail with the resin manufacturers early in the next program phase, and the most promising techniques pursued in the laboratory and on the winding machine using a simple test mandrel with appropriate curvature.

It should be noted that the worst areas for slippage are in the bow, and the use of a seperate bow module would simplify the problem by reducing its severity.

4.3.1.2 Scale Effects. It should also be noted that the severity of this problem increases with the size of the object being wound; the allowable variation in fiber path at a point on a 1 ft. diameter tube might be 5°, whereas the same tube scaled up to 10 ft. dia. might have an acceptable variation of only about 1°. The reasons for this are the reduced compaction force on the larger diameter, which affects the sliding friction of the band, and the longer time available for the band to slip on the larger object, due to the time required to return and overlay the band with the next layer, assuming the head travel speed is similar in both cases.

4.3.2 Fiberband Bridging

Bridging of fibers across low or negatively curved areas is another important concern. This bridging was evident, in varying

amounts, at the bow flare, on the main deck sheer, and at the break between decks aft. The problem at the bow was dependent on the angle and direction of fiber placement. When angles between 30 and 60 degrees were wound in the direction from the keel aft and up toward the deck, the maximum amount of bridging occurred, but when the fibers were passing from the keel up and forward towards the bow or stem, little or no problem was observed. At angles below 30°, the bridging depended on where the fibers passed over the keel and deck edge. In the bow hollow area, the lower winding angles had larger bridging deflections, since these paths tended to line up with the direction of the greatest curvature in the bow hollow. The bridging problem on the main deck, due to sheer, was inversely proportional to the winding angle, since the low angles are in the direction of greatest curvature of the sheer, and the transverse camber tends to reduce the problem for fiber paths tending more in the transverse direction.

The other major area where bridging is a major problem is the deck break aft. As can be seen in Fig. 4-11 through 4-13, at 30° there is a large amount of bridging of the fibers extending well back onto the main deck, at 45° there is a smaller but still major amount, and at 90° there is no bridging at all.

4.3.2.1 Possible Solutions. The only realistic solution seen to the major bridging problems at the deck break is to wind the hull up to the 01 level, and then cut it back to the height of the bulwark after cure. To avoid wasting the material in the deck area, it could be shaped (in the mandrel) to the form of the transom, and then cut out and used for that purpose. Since the underdeck portion of the main deck will be a separately fabricated structure anyway, extending it to the transom is not a major consideration. It should also be noted that this is a problem unique to minesweeper designs with a low working platform, and most other ships in this size range do not have the

raised deck design. The only other solution to the deck break would be to carry each fiberband down the face of the bulkhead at the break, and then staple or otherwise secure it at the deck intersection. This would result in an overly thick bulkhead unless the bands were fastened, dropped, and picked up again at the next deck level.

In the bow area, the staple or resin restraint systems mentioned for prevention of slippage could also be used to hold the bands in the hollow areas, although the use of staples for this purpose would be less desirable than resin adhesion due to the large aggregate number that would be required by the time 50 to 100 layers were wound. The other point is that the use of a separate bow module, as in the case of the slippage at the deck and stem edge, would eliminate the largest portion of the problem. The use of large pressure pads, which would have to be removed as the winding head passed by, was suggested in the earlier M-A report. While this would be a possible solution in the limited area of the bow flare, it would be cumbersome and expensive to implement, and would be extremely hard to utilize to solve the problem in the much larger deck sheer area and at the deck break. It is therefore less desirable than one of the other solutions which could be used in all of the slipping, bridging, and sagging areas.

On the main deck, decrease or elimination of curved sheer in the hull lines, increase in the amount of the deck camber, or the use of the resin to hold the bands in place would all be aoternatives. The use of tacky or B-staged resin should be tried and evaluated before any of the other steps involving limitations on hull shape are contemplated.

To demonstrate the general approach to solving this problem of placing the fiberbands on areas which do not tend to hold them in

place by their nature, McClean-Anderson performed some experiments using a roller winding head to place and flatten bands of roving on a mandrel which simulated the flat deck or topsides and a sharply radius deck edge. This work will be reviewed and photographs of the results shown in Section 4.6.

4.3.3 Sagging of Fiberbands

Recent experience of M-A in winding a boxlike structure about 8 ft. on a side, which was flat on one surface and slightly curved (3600 in. radius) on the three others, showed that if the fiberbands are rolled into place under some compaction pressure from a mechanical roller, they will adhere to the flat surface for a period of about one hour. However, without the roller pressure during application, they sagged away from the inverted flat surface after only a few minutes. This infers that if the resin had B-staged before the bands began to sag, they would have stayed in place instead of coming away from the 8 ft. wide flat surface by about 1/4 inch. The bands did not sag from the slightly curved surfaces, but these were not in the downhand position, so the exact performance there is not known. This experiment supports the suggestion to pursue the use of a roller head and quick B-stage resin system to solve the band retention problems.

It should be noted that this problem will increase with the size of the surface and the weight of the uncured or unstaged bands, and so experiments should be carried out in a manner to simulate the conditions on the ship hull rather than the model. Another contributor to this problem is the movement of uncured resin out of the matrix due to gravity or compaction pressure, since this reduces the bulk of the matrix and thus reduces compaction and tension due to winding tension over the original shape.

4.3.4 Uneven thickness Buildup

As mentioned in the discussion of the winding experiments, there is a tendency for the fiber bands to overlay each other in the ends of the hull due to decreasing girth, and also because of the paths necessary for band-turnaround if off-hull turning techniques are not utilized. This could be seen in Fig.4-8 for the 15° winding, and is shown in Fig. 4-14 through 4-16 for the turnaround areas. As in the case of the buldup due to change in girth, it will be seen that the problem increases at the lower winding angles.

4.3.4.1 Proposed Solutions. In the case of the turnaround areas, the best solution is to remove the turnaround from the hull area to an auxiliary area or extension which can be shaped to facilitate the band paths. This means extending the mandrel beyond the stern and the bow collision bulkhead, and adding a separate bow module. While this approach is not ideal from the point of view of fabricating a complete monocoque structure, it will solve far more problems than it will create, and thus is strongly recommended. The other possible option is that if a method is developed for dropping, fastening, and picking up fiberbands automatically during machine operation, there would be no requirement for turnaround, no waste of material in the turnaround areas, and the problems of incomplete or overlapping coverage in the areas of girth taper would be eliminated. It is therefore recommended that this technique also be studied and developed.

4.3.5 Edge Radius Compaction

As mentioned in the discussion of the hull shape versus normal FW shapes, the compression of the normal force caused by band tension when passing around a small radius at the deck edge or other

corner tends to force the resin out of the matrix and cause an area of reduced strength. This problem is reduced as the size of the hull increases, and is also helped if the resin begins its cure in a short length of time. It is expected that if a radius of about 6 inches is used on the full scale ship, that this will not be a problem. It can be investigated on the model by using several different (out of scale) radii, and this is also desirable because of the interrelation of this phenomena and the use of pins and/or staples at the deck edge for prevention of slippage. In general, it is not expected to be a serious problem.

4.4 RECOMMENDED MODEL DESIGN & FABRICATION PROCESS

This section will detail the fiber paths, layer orientations, roving and band sizes, hull and deck thicknesses, bow and stern turnaround area designs, bulkhead and deck integration, and reinforcement selection which are recommended for the construction of the 30 ft. model, based on the results of this study.

Because discussion of each of these recommendations would be largely a repetition of material that has already been covered, the results are presented in the form of an outline which can be used as a summary of the design and fabrication process. When added to the mandrel design discussed in the next section, and the material and process documentation in the Appendices, this summary contains a complete specification of the design of the 30 foot model and its proposed fabrication process.

As previously discussed, the work accomplished in the early part of the model phase may change some of this information or its applicability, and therefore the design information, like the material specification for the resin, should be considered a recommended starting point in the model fabrication, not a firm specification to be followed without variance.

4.4.1 Fiber Paths

a. Use helical fiber paths amidships.

b. Modify the paths as required toward the ends of the ship to keep the thickness as uniform as possible.

c. Demonstrate suggested techniques for eliminating voids and fiber buildup by:

(1) Use of unidirectional or prepreg fillers.

(2) Dropping and picking up of fiberbands.

d. Record achieved fiber path angles at each W.L./station intersection as defined by customer.

4.4.2 Layer Orientations

a. Use quasi-orthotropic layup of 0,+45,90,-45 degrees, repeating as necessary to achieve required hull thickness.

b. If possible, include some layers of +60 and -60 and/or +30 and -30 degrees, to demonstrate applicable techniques.

4.4.3 Roving and Band Size

a. Based on the scaling of the full scale ship, use the following roving size(s) and bandwidths, adjusting as necessary based on dry and wet winding experiments:

ITEM	SHIP	MODEL
Roving yield, yards/lb.(t)	113(.09")	675(.01")
Alternate yield (handling)	225(.06")	-----
Alternate yield (thickness)	-----	450(.03")
Bandwidth, approximate	24-40"	5-8"

4.4.4 Winding Thickness

a. Structural analysis:	SHIP	MODEL
Hull/Deck	5"/4"	1"/.8"

Alternate: Use thicker winding to demonstrate full scale winding problems associated with cure cycle.

4.4.5 Bow & Stern Design

a. End bow at collision bulkhead, and extend mandrel for turnaround.
b. Extend stern past transom and shape mandrel for turnaround.
c. Extend 01 deck to transom, and cut off down to bulwark in way of aft main deck after cure.
d. Wind transom into 01 deck area extension, and cut out after cure, and bond and bolt to shell at stern.
e. Hand laminate bow section and bond and bolt to hull at collision bulkhead.

4.4.6 Bulkhead and Deck Integration

a. Omit main deck forward of weather area due to space limitations in mandrel.
b. Omit every other bulkhead to reduce cost and improve access for mandrel removal.
c. Develop and demonstrate several different bulkhead attachment designs at the several bulkheads.
d. Include or omit main deck aft at customer's option.

4.4.7 Materials

a. Use materials as specified in the Appendix to this report, except as directed by customer.

4.5 MANDREL ANALYSIS & DESIGN

This section will discuss full scale mandrel concepts, related model mandrel concepts, the preliminary design of the model mandrel, and alternative model mandrel concepts.

4.5.1 Full Scale Mandrel Concepts

4.5.1.1 Rotating Axis Mandrel. Various concepts for a full

scale mandrel for a rotating axis machine were considered. It quickly became apparent that the two principal design problems are: (1) the high stiffness/low deflection required as the fully loaded mandrel rotates in the machine, and (2) the necessity to disassemble the mandrel structure after laminate cure and remove it through the limited number and size of openings available in a monocoque hull structure. For purposes of conceptual design, it was assumed that the best stiffness to weight ratio would be achieved by a space frame structure fabricated of steel pipe sections. Sections would be pinned and bolted together through the bulkheads and decks, which would be pre-manufactured and installed into the mandrel before winding. Construction of the frame would be limited to structural elements which would pass out through the uptake openings and bulkhead doors.

In order to achieve the minimum weight possible, the pads or forms which form the contour of the hull should be as thin as practical, both to limit their own weight, and to leave the maximum amount of space for the supporting space frame. A section of such a truss structure is shown in Fig. 4-17. The decks in the sketch are shown as integral with the skin winding, which was one of the configurations considered and not selected for the winding, but the general nature of the space frame is unchanged. There are separate frame modules in each compartment between bulkheads and decks. The necessary pin and bolt connections, which would require collars to prevent compression of the deck and bulkheads under mandrel loads, are not shown.

The weight and size of the mandrel structure was estimated in connection with the design of the model mandrel, which will be discussed in Section 4.5.2. This was accomplished by scaling up the weight of both the filament wound hull and the mandrel, and then checking the full scale mandrel deflection against the size of the space frame members, and correcting those sizes until the

deflection was acceptable, as discussed in Section 4.5.3.

Since the scantlings of the 30 ft model were determined by scaling down geometrically from those determined in Section 2 for the full scale ship, the weight of the model hull was simply scaled back up to ship size in the same manner. This accounts for the weight of the basic hull, deck, bulkheads, and mandrel, but does not include any other weights which might be decided to be included in a full scale mandrel for production reasons. This weight was then used to check the deflection of the full scale mandrel against the criteria of 0.1% maximum fiber deflection prior to cure. It was assumed, as in the design of the model mandrel, that the critical layer was a 0° winding which assumed the approximate shape of a catenary with the same deflection at the center of the hull as the deflected mandrel. This allowed estimation of the fiber stretch for a given mandrel deflection. The mandrel deflection calculation was conservative, in that it assumed beam bending with the upper and lower flange areas equal to the cross sectional area of the structural pipes at the top and bottom of the mandrel. The diagonal members therefore were assumed to carry only shear loads. This conservatism compared to the deflection of the actual space frame structure was assumed to offset some of the weights which would probably be included in a full scale mandrel, but were not considered in this concept design.

The result of this scaling is a hull weight of 505 kips, and a mandrel weight of 381 kips, for a total combined rotating weight of about 887 kips. The individual pipe sections were estimated to weigh 210 lb per 8 ft length, which was considered to be feasible for 4 men or two men with a portable hoist to handle. This full scale mandrel represents a massive piece of hardware, and could cost in the neighborhood of a million dollars. It therefore seemed reasonable to investigate the possibilities of a fixed

mandrel design, where the machine head rotated around the axis of the mandrel, which could then be supported at several locations by hydraulic or otherwise movable supports. These could then be retracted as the winding head passed by, and re-extended to again support the hull winding and mandrel until the next pass of the winding head.

4.5.1.2 Ring Winder / Fixed Mandrel. Because the mandrel required for a ring winder does not rotate, and may be supported at least intermittently between the ends, it has the same requirements as the rotating mandrel discussed above except for the bending load. Therfore it is a less demanding structural design problem. The amount of bending material which could be removed from such a mandrel would be a funtion of the design of the ring winder bed, the number of winding head rings, and the feasible number of mandrel supports which could be used to reduce the distance between supporting points. Another complication is the design of the supports which would have to bear against the uncured windings, including the acceptable bearing pressure and therefore area of the support, design of the bearing area inside the mandrel, and related winding cure considerations.

Since the design of such a ring winder is not within the scope of this investigation, and because no current winder could be found which would offer the possibility of scaling to ship size, the design of a mandrel for a rotating ring winder was not pursued further at this time. Certainly a design study of such a winder would be required before its approximate characteristics could be identified, including the required configuration of a compatible mandrel.

4.5.2 Related Model Mandrel Concepts

Based on the general configuration of the full scale rotating

mandrel discussed in the previous section, a preliminary design for a model mandrel following the same concept was prepared. This was done so that the model mandrel and winding techniques would be representative of the full scale facilities required to wind a ship in the same manner.

As in the case of the full scale mandrel, the limiting design considerations were the acceptable deflection during rotation, and the ability to disassemble the mandrel after the hull has cured.

4.5.3 Model Mandrel Design

The 30 ft model mandrel design is shown in Fig. 4-18. As will be seen from the drawing, the major structural element of the mandrel is a space frame constructed from square steel tubing longerons at the four corners, and smaller steel tube frames welded transversely and vertically between the longerons to form a box shaped space frame. The frame is stiffened by diagonal truss members, also welded for rigidity, and is tapered at the ends to stay within the hull envelope. An 8" dia. pipe shaft is fastenened to each end of the frame by bolted flanges, and in turn supported in the winding machine auxiliary bearing foundations. It will be noticed from the drawing that the frame and shaft axis is not at the center of the hull section, but is raised to allign it with the transom opening, through which it will be removed. Unlike the full scale mandrel concept, the frame is continuous throughout the length of the ship, and not built up of sections bolted through the bulkheads. Instead, the bulkheads have larger-than-scale openings, to allow personnel access for disassembly of the frame from the hull contour blocks.

The actual hull contour is formed by blocks of lightweight (4 lb./cu.ft.) rigid plastic foam, with a layer of heavier (8

lb./cu.ft.) foam which is contoured to the ship lines. This is then coated with a surfacing compound to provide sufficient strength to support the compression of the first layers of windings. The inner foam blocks are bonded to aluminum sheets which are in turn fastened to the space frame with support angles and sheet metal screws. In a similar manner, the bulkheads are supported to the frame with plate clips which are screwed to the frame and through bolted to the GRP bulkheads.

It will be noted that the main deck and some of the bulkheads have been omitted, compared with the full scale ship. This was necessary to provide access to the interior for disassembly, since the scaled 'tween deck height would be only 18".

After assembly of the bulkheads and foam blocks to the mandrel frame, additional blocks for the turnaround areas are added, and the foam shaped to the contour of the molded lines, either by hand working, or preferably by a cutting head mounted on the winding machine and programed to the contour of the ship.

When winding and curing are complete, the turnaround areas and shape blocks are cut away from the exterior, providing access to the bolting flanges on the pivot bearing shafts. After supporting the hull in a cradle assembly, these shafts are removed, providing access to the interior. Starting at the transom end, workmen can crawl inside the mandrel frame and release the block and bulkhead clips by removing the tapping screws. At this point, shims separating the blocks and bulkheads from the frame are removed, and the frame can be slid out of the tramsom opening and removed.

The foam blocks are still inside the hull, and they are then removed by cutting into pieces small enough to pass through the bulkhead openings, and are thereby destroyed in the process. In

the full scale hull, the contour pads would be pinned in place, and removed intact in pieces of a size to pass through the doors and uptakes, and then reused for the next hull.

4.5.3.1 Model Mandrel Design Analysis. In order to size the structure of the mandrel, an estimate of the hull and mandrel weight was made, and the mandrel designed to provide a beam deflection resulting in less than 0.1% lengthwise deflection in the outer winding of the hull (assumed to be axial for the worst case). Because time did not permit an accurate analysis of the space frame, it was assumed that only the longerons were effective in bending, and that the worst deflection occured at a rotation angle of 45°. Using stress and deflection analysis for a beam, and assuming that the diagonals and transverse members were effective in shear but did not contribute to bending stiffness, several estimates of frame scantlings and weight were made to arrive at the configuration shown. Based on the weight of a 1/2" laminate, the bending deflection was calculated to be 0.5", resulting in a catenary deflection of the outer fiber on the hull of about 0.01% of its length. Later in the study it was determined that the hull winding would be more on the order of 1" in thickness, adding another 2022 lb to the combined weight.Since the calculations were conservative by the beam assumption compared to the actual space frame, and the calculated fiber deflection was 1/10 of the allowable fiber stretch, the mandrel design was not revised, and is still considered to be conservative. At the beginning of the next phase of the program, an accurate deflection and stress calculation for the space frame should be made using the assigned laminate thicknesses and specific gravity based on expected glass content. The sizing of the structural elements can then be re-examined before detailing the final mandrel shop drawings. The estimated weight of the hull winding, at 1" thick, was 4286 lb., and the mandrel structure complete was 7643 lb.

4.5.4 ALTERNATE MODEL MANDREL CONCEPTS

The model mandrel concept discussed in the previous section was designed to be a subscale representation of a full scale mandrel, in order to demonstrate the full scale concept. It is therefore really a reusable structure, with the exception of the foam contour blocks, since the full scale mandrel is by design a reusuable fabrication tool.

In order to reduce the cost of the model construction, it would be possible to design an all-throwaway mandrel which would be less costly than the welded steel tubing design. This could consist of a stressed skin plywood structural box, designed to fit within the contours of the hull lines, or a series of such boxes, with the bulkheads sandwiched between them. The boxes could be bolted together through the bulkheads, as in the case of the full scale mandrel, and be larger in cross-section than the steel model truss in Fig. 4-18, since it would not have to pass through a bulkhead opening.

The plywood box structure would then be covered with foam blocks, and contoured to shape as in the primary concept. After winding and cure of the hull, the box structure and the foam would be cut up with portable panel saws and passed out through the bulkhead and uptake openings.

It is suggested that a cost tradeoff for this concept be made early in the next phase, before deciding whether the added cost of a steel mandrel is justified for demonstration of full scale concept purposes.

4.5.5 MANDREL DESIGN CONCLUSIONS

As a result of these studies, it is obvious that the design,

construction, and handling of a full scale rotating mandrel will be a major project due to its great size and weight. It is therefore suggested that a preliminary design of an alternate fixed mandrel ring winder should be developed, so that a valid trade-off study between the two options can be made.

It is not necessary that this be done before winding the model hull, but doing so would have the advantage of assuring that the methods used for the model could be held up as a demonstration of the full scale machine and mandrel techniques. It should be noted, however, that the ability to filament wind a hull successfully is primarily a question of the winding head design, control techniques, and material/cure characteristics. The exact form of the machine structure supporting the winding head is a separate problem, although admittedly it is one that could have a large bearing on the cost, and therefore feasibility, of the entire project.

From a winding point of view. the choice between a rotating and fixed mandrel is not a clear one, since each has its drawbacks. The major problems with the rotating hull are the stiffness requirements already noted. A disadvantage of the fixed mandrel is the fact that the critical bottom structure or deck is always in the downhand position, complicating the sagging problems and tendency for resin migration in the sides of the hull. With a rotating mold the force of gravity acts in a sinesoidal manner, alternately tending to#sag and compress the winding. It is therefore expected that the sagging and migration problems would be less severe in the case of the rotating mandrel.

4.6 WINDING MACHINE CONSIDERATIONS

This section will discuss the relative merits of the identified machine concepts, the related model scale machines, and the cost

of modifying existing machines to the capabilities required for the winding of the 30 ft. model.

4.6.1 Full Scale Machine Concepts

This section will review the winding machine concepts which were considered during the study. Since the major problems and advantages of the two primary concept have of necessity been discussed in the previous sections on mandrel design, this section will be limited to a summary of the identified full scale machine concepts, and the apparent advantages and disadvantages of each.

4.6.1.1 Rotating Horizontal Axis Machine. This is the normal filament winding machine configuration used in the past for many applications, including the 10 ft model studies and experiments for this report.

Advantages:

(1) Since it is basically the same as current technology, it will be the be the most easily designed, and will have less developement associated with its production.

(2) The winding techniques associated with such a machine are in large part developed, resulting in a higher degree of confidence in the success of the winding process developement.

Disadvantages:

(1) The weights of the mandrel and winding increase as the third power of the length; thus the bending design problem increases with size, particularly in terms of handling the weight of the rotating mandrel and its disassembled components.

(2) The torque requirements of the rotating mandrel resulting from off axis weight (the ship axis and mandrel axis are not simultaneous due to the hull

shape) requires careful counterbalancing before and during the winding process to avoid excessive torque loads on the machine.

(3) As the mandrel rotates, there is a tendency for the bands to sag as they rotate to the downhand position. (Of course they also have a tendency to compress when in the top position).

4.6.1.2 Fixed Horizontal Axis Ring Winder. This is the ring winder discussed in the sections above. In this concept the mandrel is fixed in position, with sufficient space underneath it for a vertical transverse ring track to pass along and over the length of the hull. This track contains one or more winding heads which apply fiberbands to the hull in a circumferential manner, while at the same time the ring track moves along the length of the hull in horizontal tracks on the floor. The relative speed of the winding head in the ring and the ring on its track determines the fiber path, with 0° yielding all movememt in the direction of the floor track (except for movement in the ring head to contour to the longitudinal curvature of the hull), and a 90° path yielding all movement of the head in the ring (with the exception of band pitch advance).

Advantages:

(1) Overcomes the mandrel bending problem, assuming that intermediate hull supports are used to carry the weight of the mandrel (except when the head(s) passes).

Disadvantages:

(1) More complex than the rotating axis winder, because of the complexity of the ring track and winding head drives, fiber feed mechanism, including resin feed, and because of the requirement for retractable mandrel supports. These supports will will have to be controlled by the machine microprocessor, adding another degree of freedom and for both control and power drive,

and will have to be carefully designed to avoid placed excessive load on the uncured resin. Additionally, the support positions will have to be continually varied for the changing winding thickness, although this could be accomplished with pressure sensing.

(2) The sagging of the fibers on the downhand side (bottom) of the mandrel will increase since they will always be in this position.

(3) Resin migration in the side of the hull will increase, unless the resin used is of the quick B-staging type, since there is no reversal of gravity forces by rotation.

(4) Inspection and manual intervention of the winding layup on the bottom will be much more difficult, due to the downhand position.

4.6.1.3 Fixed Axis Vertical Winder. This concept has been used successfully by Lockheed and others to eliminate the mandrel bending and fiber sagging problems associated with a horizontal axis.

Advantages:

(1) Overcomes bending problems due to gravity forces.

(2) Overcomes transverse resin migration problems due to gravity.

Disadvantages:

(1) Longitudinal resin migration problems are introduced due to gravity.

(2) Due to size of ship contemplated, machine is the height of a 20 story building, introducing an additional facility cost. This has been accepted in the past for certain applications, such as vertical assembly of missiles and the space shuttle, but is an expensive alternative. Inspection access during winding also requires an elevator stage, with horizontal movement

added to get close to all areas of the hull.

(3) Erection of the mandrel and de-erection of the completed hull would be major operations, possibly requiring bending stiffness in the mandrel, which would negate one of the major advantages of the concept.

4.6.1.4 Internal Axis Winder. This concept is arguably not even a form of filament winding, but is of interest because of its relationship to the other concepts discussed, and the possible eventual developement of automatic cloth layup machines as extensions of the semi-automatic machines now used by the Italians and others for resin wetting and placing of woven GRP fabrics into ship hull molds. In concept it would be like a horizontal axis filament winding machine, except the winding head would travel inside of a female hull mold, instead of outside of a male hull plug or mandrel. The fibers would not be "wound" onto the mandrel, but would be placed into position in the mold by a rolling contact winding head as discussed in Section 4.3.3. If it turns out that it is necessary to develop this technique to successfully wind flat or hollow surfaces on the outside of a hull, then it would be only a small advance in technology to apply the technique to the entirely concave surface of a hull.

Advantages:

(1) Would provide a smooth outer surface, eliminating filling and finishing requirements that may be required on a large (externally) filament wound hull.

(2) Would allow access for conventional fitting out and installation of systems, since the hull and deck would be wound seperately to provide the required access for the winding (or laminating) machinery and head.

Disadvantages:

(1) Requires developement of roller winding head technology capable of following all of the internal contours of a ships hull.

(2) Requires secondary bonding of decks, bulkheads, and framing, since they would be in the way of the winding head if placed in the mold ahead of time.

(3) Machine would be useful only for laminating open shapes, and could not be used for winding large cylindrical shapes other then ships, as could a conventional winder.

4.6.2 Model Winding Machine Concept & Cost

In reviewing the results of the previous work on the machine and mandrel concept for the full scale ship, and the mandrel concept for the rotating axis winder, it became obvious that there was not sufficient information available on the configuration, design, and cost of a ring type winder to consider it in detail within the parameters of this study. It was therefore decided that the only viable concept for winding the 30 ft hull that could be successfully addressed was the use on a conventional existing ring winder, modified as necessary to accomplish the winding of a 30 ft hull.

Examination of the dimensions and characteristics of the McClean-Anderson W60 winder, and discussions with McClean-Anderson, led to the conclusion that this machine would be suitable for such a project, after certain modifications. These modifications are as follows:

(1) A mandrel support system consisting of head and tail bearing blocks raised off of the floor to provide sufficient clearance for the mandrel rotation. This would include an offset chain drive system to connect the machine output shaft with the mandrel shaft, and to modify the speed to allow the winding of low angles.

(2) A more powerful tensioning creel stand with the ability to handle the size, number, and tension of the fiber bands

envisioned. This would be mounted on a seperate carriage and rails from the existing system, would would still be used to support and position the winding head.

(3) Modification of the existing crossfeed unit to a heavy duty configuration capable of handling the expected loads.

(4) Increase of the capability of the controller unit memory and disc drive storage unit.

Based on this list, an estimate of the cost of these modifications was prepared by McClean-Anderson, and is summarized below:

(1) Mandrel support system	$ 64k
(2) Heavy duly crossfeed modification	$ 20k
(3) Tensioning creel stand, for (4)	$122k
(4) Carriage, rails, drive, controls, for (3)	$ 90k

The upgrade of the controller unit is already scheduled, and the cost is therefore not included in this projection.

4.6.3 Roller Winding Head Experiments

In connection with the investigation of the modifications necessary to make the M-A machine compatible with the requirements for winding a 30 ft model, McClean-Anderson ran an experiment on the use of a roller winding head to compact the fiberband against the mandrel and thus help prevent sagging of the bands. These evaluations were made on a plate mandrel having one flat surface and one with an 1800 in. radius curvature. The edges between the flats had a 3 in. radius. The mandrel was 4 ft long, with a total swing of 64 in.

The masonite mandrel was mounted in a three axis W-60 winding machine, with the crossfeed of the head controlled by a piezoelectric pressure sensing device. This permitted the winding head to follow the motions of the plate as it rotated, and to apply an adjustable pressure to the roller/mandrel interface. Besides the

roller, the winding head included a comb to space the fibers. Fiber tension was obtained with friction devices in the resin proportioning and impegnating device.

Eighteen rovings of 675 yield were used to form a 2 in. wide band. Epoxy resin content was approximately 50%. The roller pressure was kept at 15 lb, which resulted in about 5 psi on the band and surface of the mandrel. The winding was done with a circumferential winding program at a speed of about 50 ft per minute. Band thickness was 7 to 8 mils.

As shown in Figure 4-19, the fibers were deposited in a very even manner, and stayed in position as the mandrel rotated. When the bands were placed on top of one another, there did not appear to be any distortion of the wet bands underneath. The top band was not as smooth as the first one applied directly to the masonite, however. There did not appear to be any problems with fibers adhering to the roller, which would have caused difficulty in maintaining uniform bands.

The equipment definitely improved the quality of the fiberband placement on the mandrel, although it could only be demonstrated on radial windings due to limitations in the movement of the head. This could be solved by adding an additional motion axis to allow the head to remain in contact with the mandrel at low winding angles.

It appears that the concept of a roller head to apply fiberbands to the surface of a hull is feasible, and results in an improved winding. The winding head may require a second roller to flatten the bands after they are placed on top of previous windings, and there may be a requirement for groomed or scraped rollers, since polyester resin is more prone to sticking to the winding equipment than is the epoxy resin which was used for this experiment. This also infers a trade-off between a resin that does not stick

to the rollers, and one that does stick to the mandrel and hold the fiberband in place.

4.7 CAD/CAM SIMULATION OF FILAMENT WINDING

During the early stages of the project, when means of determining fiber paths on the hull and documenting these paths on a drawing were being developed, it was suggested by project personnel familiar with the use of Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM) systems, that it might be possible to develope filament winding paths on such a system. This would eliminate or greatly reduce the amount of manhours spent in the laboratory or winding shop developing these path on the mandrel by manual or manually controlled techniques.

To investigate this possibility, the offsets of the MCM-1 were input to the Lockheed CADAM system from a standard CAD terminal, and then an advanced 3D graphics and fairing package used to develop and fair curves through these points. The offsets used were those from the building yard, and thus they had been corrected to the usual tolerances for such mold lofting, on the order of the nearest 1/16th of an inch. The 3D fairing program used, however, is designed to much closer aircraft tolerances, and therefore automatically adjusted the input to its own curve-fit tolerance. The result was a 3 dimensional model stored in the computer, in full scale on a 20,000 inch square drawing field. This model could then be projected on the CAD screen in any scale desired, rotated about any of the three axes desired, and a plane passed through it in any direction which described a curve of the true hull shape in that plan. A reduced size body plan and a rotated projected outline of several hull stations, the keel and stem, and deck edges is shown in Figure 4-20.

It will be seen that if the plane passed through the hull was in

the momentary axis of the movement of the filament winding head, a tangent to the resultant curve in that plane would be a description of the filament path between the mandrel and the winding head at that point in the winding (for the described angle of rotation and machine head movement). If a distance along the tangent is defined, then a resultant point in space can be found which will describe the position of the machine head. This is all within the current capability of the CADAM system amd programs.

It will also be seen that if this procedure is repeated at small increments along the winding path, determined by proceeding for a short distance parallel to the previous path of the same layer, a series of points will be defined which will be the track of the winding head as it proceeds along the hull in a given winding layer. Thus by starting with a plane at the desired winding angle, and proceeding in a series of small steps around the hull, the history of the required head positions could be established on the computer, to a greater degree of accuracy than could be accomplished on the winding machine. Of course, no information on slip angles or other problems would be generated, but in time these paramenters, or limits associated with them, could probably be included in the machine routines.

The next step would be to translate this information on head position relative to mandrel rotational position into a form which the filament winding machine could understand. This is the pupose of the CAM portion of CAD/CAM systems, and is done automatically by a digital processor, based on coded instructions about the machine and part paramenters which are input by a manufacturing engineer expert in CAM systems. The Lockheed W-60 machine is currently being fitted with a controller which is compatible with this system, and therefore will be compatible with such an approach in the future.

In order to accomplish such an automated system of developing filament winding machine instructions, it will be necessary to develope subroutines for the CADAM sytem which would automatically and repetitively compute the required fiber and machine head positions. This has been investigated, and there does not appear to be any basic problem in accomplishing such modifications. The cost of this effort has not yet been established, but it is being investigated as part of Lockheed's continual improvement of their design and manufacturing capabilities.

4.8 FULL SCALE PROBLEMS

This section will discuss the problems associated with scaling the techniques and designs developed or recommended for the 30 ft model up to the size of full scale ship. Areas covered include the winding patterns and techniques, the resin system and its cure characteristics, methods of applying a smooth surface finish to the laminate, access to the interior of the hull after winding for removal of the mandrel and completion of the ship, and the questions involved in scaling the design of a winding machine up to the projected ship size.

4.8.1 Winding Scale-up Effects

Winding scale-up effects which are anticipated include different slippage characteristics, different bridging and sagging characteristics, and different corner compression problems.

4.8.1.1 Fiberband Slippage. As discussed in Section 4.3.1.2, the slippage angle limits which are observed on a shape 12" in dia might be on the order of 5°, while the same shape increased to a size of 10' dia would have a slip angle limit closer to 1°. As previously pointed out, the large size of the full scale hull may result in almost no margin on the acceptable angle which will

prevent slipping at a particular point on the hull.

For this reason, among others, it is considered that a method of restraining the fiberband in position until the resin is sufficiently cured to restrain it will be a necessary precursor to the successful winding of a large hull. It should also be noted that whatever system is developed will have to work for the number of successive layers in the final full scale hull, whether it is closer to 50 or 100.

4.8.1.2 Bridging and Sagging of Fiberbands. There are several aspects to the problems of bridging and sagging which may not scale directly to as full scale hull. To begin with, the forces which cause these problems are a function of band weight, tension, mandrel curvature, and the surface area over which any restraining force based on resin viscosity acts, as discussed in Section 4.3.3. Since all of these factors do not scale in the same proportion, and the resin characteristics may not scale at all (i.e. may be the same for both model and ship), the bridging and sagging characteristics will be different on the ship.

In the case of bridging, it is caused by the weight of the fiberband, and resisted by the viscosity of the resin. If the resin is the same on the model and ship, it is clear that the sagging problem will be worse on the ship, due to heavier fiberbands and longer dwell times at the mandrel rotational position where bridging is a problem, i.e. downhand (fibers hanging below the mandrel).

Another problem is that if staples or other mechanical means to resist sagging are used, the restraining force may not increase at the same rate as the fiber weight, in scaling from model to ship. This is another reason to believe that the use of a high viscosity or "sticky" resin, or a means of quickly B-staging the

resin before the mandrel reaches the sagging position in its rotation would be a desirable approach.

Bridging across a hollow in the bow or the deck sheer is a function of the rate of curvature and the fiber tension. As the ship size increases, the curvature of the problem areas decreases, and the band tension will increase, although not necessarily by the amount of the scale ratio. Thus there is reason to believe that the problem may actually be less serious, or at least no more so, on the ship than on the model. This is one reason why scaling the fiberband size on the model down from the maximum size possible on the ship may be a good procedure, since it will tend to keep these problems as nearly to scale as possible, and decrease the chance of unpleasant surprises when scaling up to ship size.

4.8.1.3 Corner Compression. As discussed in Section 4.3.5, the problem in passing the fiberbands around sharp radii is that the transverse force due to fiber tension tends to compress the laminate and drive out the resin, resulting in a locally weak area due to resin starvation. As was pointed out in that discussion, as the size of the ship increases the radii at the deck edge and other corners can be increased to the point where the fiber tension is no longer producing an excessive force, and the problem will no longer exist. This can be investigated on the model by including some full scale radii, or at least some which are appropriately scaled to the fiberband size and tension.

4.8.2 Resin System Differences

As discussed in Section 3, the desirable viscosity for a filament winding resin is determined by the desire to obtain complete wetting of the fibers during their dwell time and rolling or wiping in the resin bath. As the size of the fiber strands in-

creases, the surface area decreases for the same cross-sectional area, so it is possible that the viscosity can be increased on the ship, although the resin characteristics at winding are probably otherwise generally the same. If a higher viscosity is used to help maintain fiber position, it may be possible to develop pressurized impregnation nozzles that will saturate the fiber with a metered amount of resin despite a higher viscosity. This should be investigated as part of the large ship fabrication developement.

The second aspect of the resin scaleup is the cure cycle, since the time between winding head passes will be greater, because the speed which can be used will not increase at the same rate as the scale of the winding. It would therefore appear that the cure cycle should be slower on the ship, to assure primary bonding of the next layer. The only problem with this approach is that the sagging discussed in Section 4.8.1, which is also a function of time, grows worse as the time span increases. Again, the solution that suggests itself is a resin system which B-stages quickly to hold the fiberbands in place, but does not cure until the next layer has been wound on top of it, assuring a good primary bond.

The last scaling problem associated with the resin system is the exotherm due to the curing reaction. Since the amount of heat generated is a function of the amount of resin, it is proportional to L^3, while the cooling of the winding is a function of surface area or L^2. This means that either the rate of exotherm has to be slowed down in a thicker winding, or the rate at which heat is carried away has to be increased by faster airflow over the surface the surface, cooler air, or some other variable. If the longer winding time allows for greater time between layers, the cooling may not be a problem, but it will have to be considered in selecting and controlling the resin cure cycle for the ship. This is also a problem which may be addressed in the labor-

atory with a smaller full thickness winding, and this is recommended as a desirable step before proceeding with the full scale winding planning.

4.8.3 Surface Finish Concepts

It is recommended that the model be at least partially finished to a smooth surface by the application of a troweling compound consisting of a resin and filler material such as glass microballoons. Since the roughness of the outside of a filament wound hull is probably roughly proportional to the fiberband thickness and number of layers, it will probably be greater in the ship than the model by a significant amount. Also, in the case of the ship, anything used to coat or smooth the surface of the winding will have to have sufficient elasticity and strength to withstand the dynamic pressure loading associated with UNDEX loading and local docking or grounding loads. Because the surface area increases as the square of the scale ratio, the amount of manhours in troweling and smoothing the surface will be significant. For this reason it is recommended that the developement of an automated method, such as spraying of the surfacing compound, followed by machining or grinding with a tool attached to the winding head, be investigated. This technique could be developed at the model scale, to demonstate its feasibility.

Another technique which has been suggested is the application of a tightly stretched or wound film placed over the surface after application of a finishing compound, with the tension in the film tending to smooth the surface. While this is similar to the techniques proposed for an aircraft fuselage, it is dependent on the normal force developed by the film tension, and thus would not be very effective on a large flat area such as the deck or topsides for the same reason that sagging of fibers is a problem on such surfaces.

4.8.4 Machine Scaleup Problems

As discussed in Section 4.6, the scaleup of the machine design is complicated by the fact that the mandrel weight increases as the cube of the scale ratio. The possible solutions to this problem have been covered in that section, and will not be repeated here.

Another machine scaling problem which has not been discussed, however, is the magnetude of the materials handling problem that would be introduced by winding a full scale hull. The rate of application of materials to the model size mandrel is within the current experience of the industry, but the rate at which fiber and resin would be consumed in laying down one or more bands of the size contemplated would involve a major logistics effort. An adequate quality control program would complicate the problem by defining the temperature of the resin, the limitations on interruptions of the winding and cure process to assure promary bonds between layers, and other parameters associated with time and materials control. This problem should be studied by analyzing the rates and control parameters involved involved in such a process, and estimating the facilities and procedures required.

A third consideration in the scaling of the machine is the size and cost of the facilty necessary to contain and support it. It is not clear at this time if such a facility would be in a shipyard, and devoted entirely to ship hull production, or if it would be more of a filament winding facility which could handle ship hulls and any other quasi-cylindrical object such as railroad cars, cargo containers, material hoppers, etc., and thereby stand a greater chance of having a high rate of utilization and therefore lower capital costs associated with any one product. This is another subject that should be studied before valid cost estimates for a full scale hull can be developed.

4.8.5 Interior Access Scaling

As discussed in Section 4.5, the access required into the 30 ft model is related primarily to the removal of the mandrel, and any labor associated with the bonding or fastening of the bulkheads, deck, transom, and bow module. In the case of the full scale ship, the access problem is much more significant.

The first major difference is the access required for installation of the major machinery components. Except for those that can be lowered through the machinery uptake openings, these components will either have to fit through the bulkhead watertight doors, or there will have to be bolted patches in the bulkheads or decks for their installation and removal for servicing and replacement. Once a design is established for the MSH, the detailed plans could be used for an access study to define these problems and recommended solutions. This should include consideration of access for construction and outfitting personnel, since it has been shown in many repair studies on steel ships that the extra cost of cutting hull openings, and rewelding them after repairs to the ship, saves more manhours than it expends. Since the FW hull cannot be welded, such solutions will have to be anticipated, and provisions for the construction and maintenence access provided in the basic hull design.

Later in the program, after the cost, weight, and feasibility of secondary bonded and bolted joints has been established, the access problem should be reexamined to see if the concept of an integral deck is still the most cost effective overall solution.

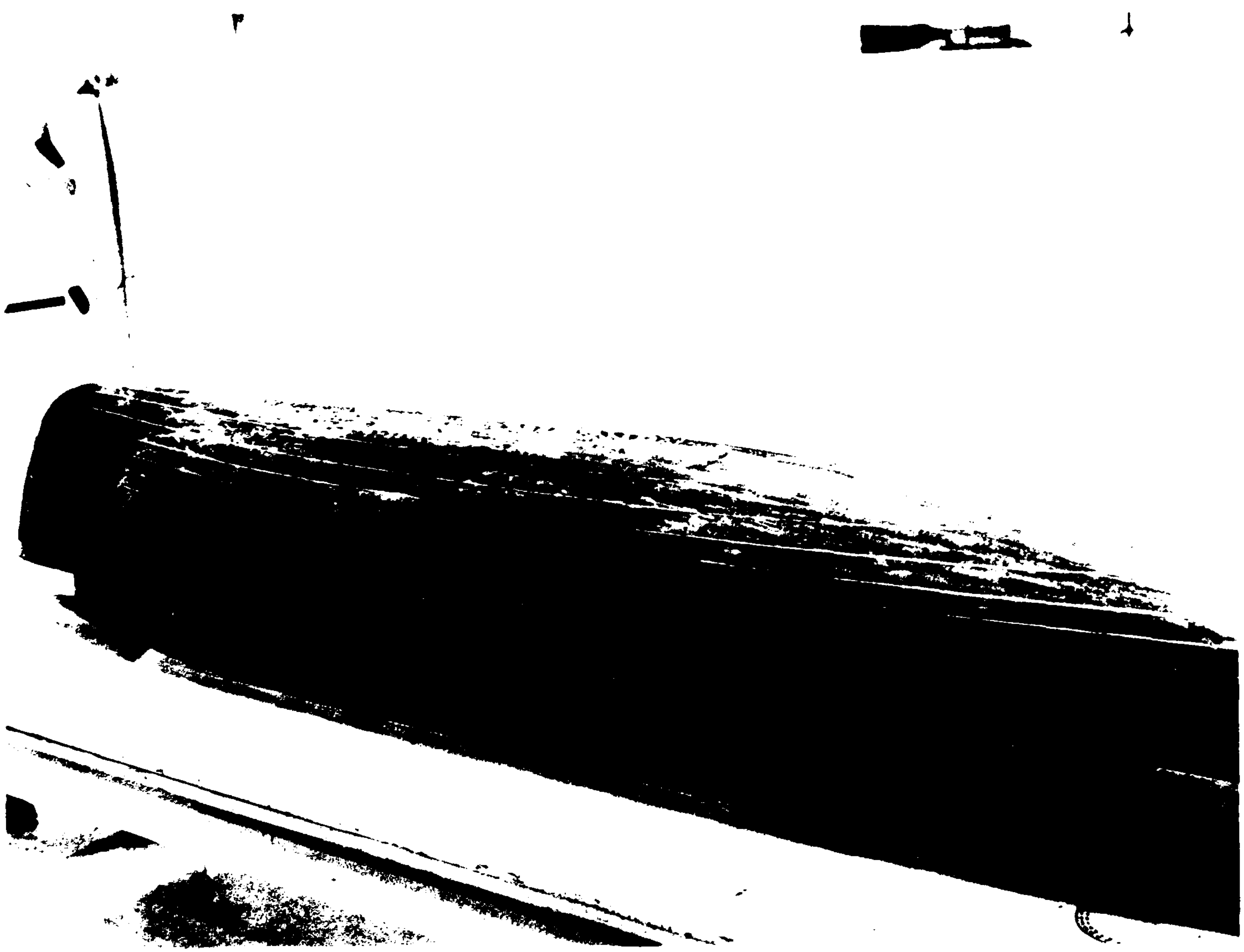


Fig. 4-1 1/20th Scale MCM-1 Hull Model

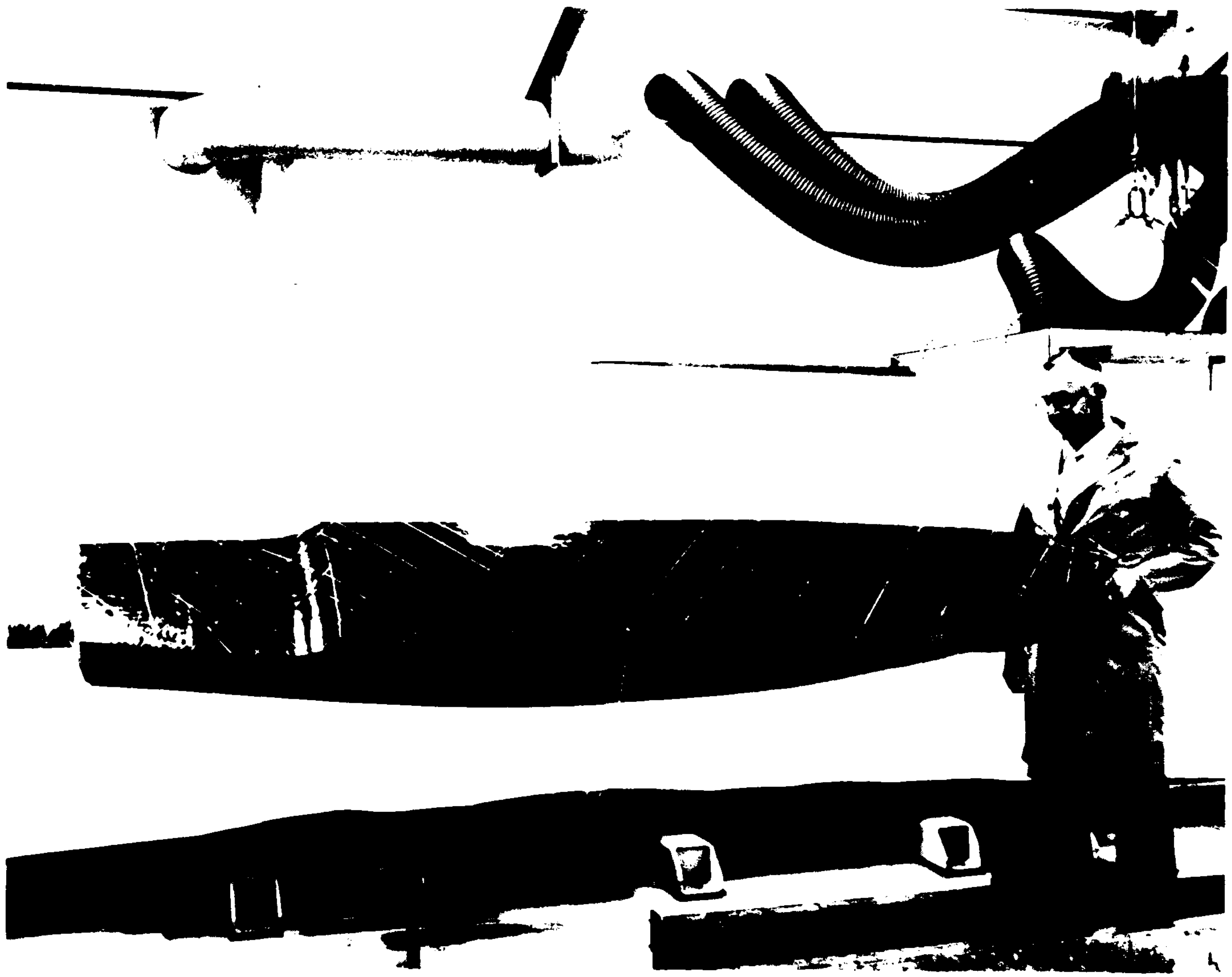


Fig. 4-2 Hand Winding Experiments - Deck View

Fig. 4-3 Hand Winding Experiments - Bottom View

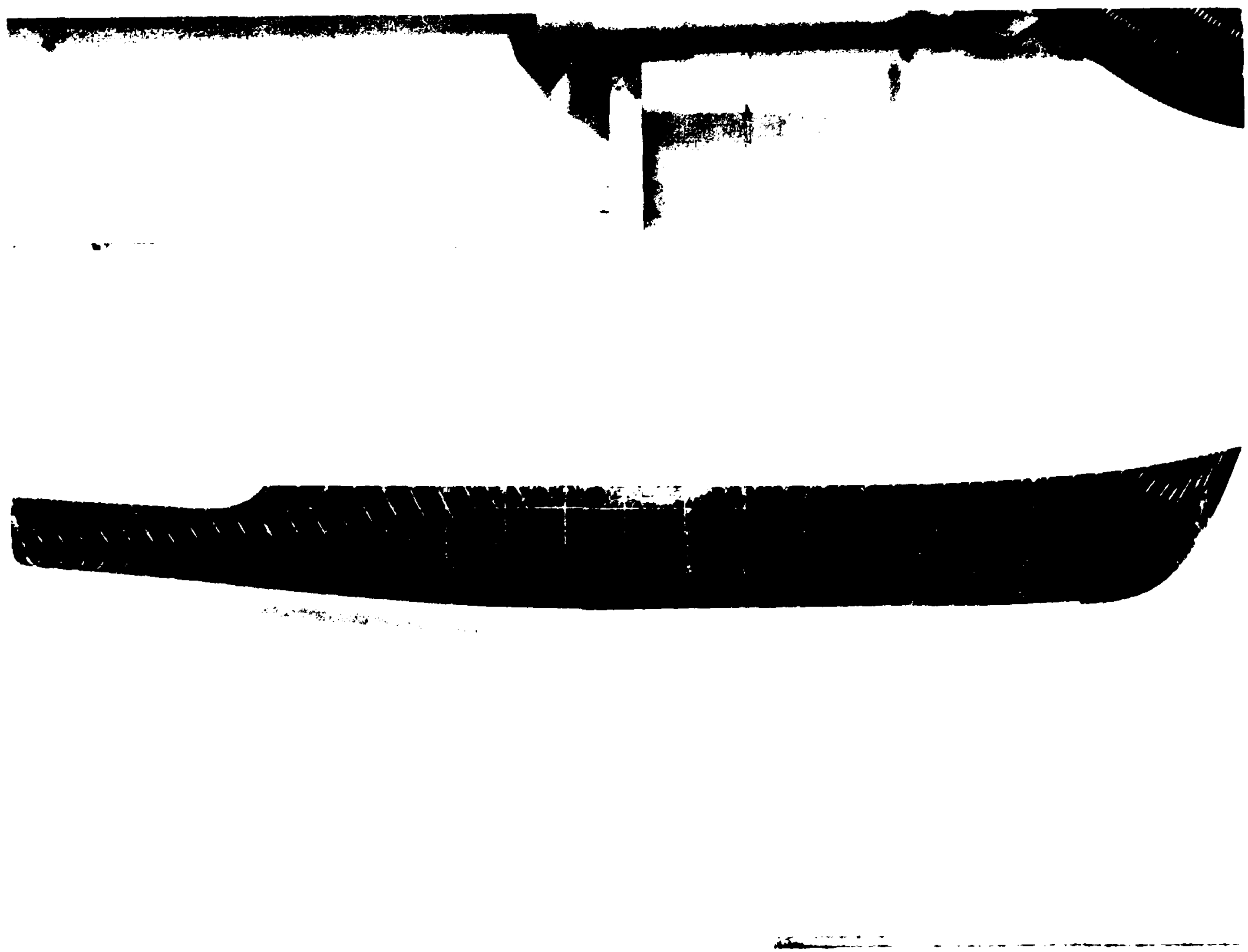


Fig. 4.4 60° Winding Experiments

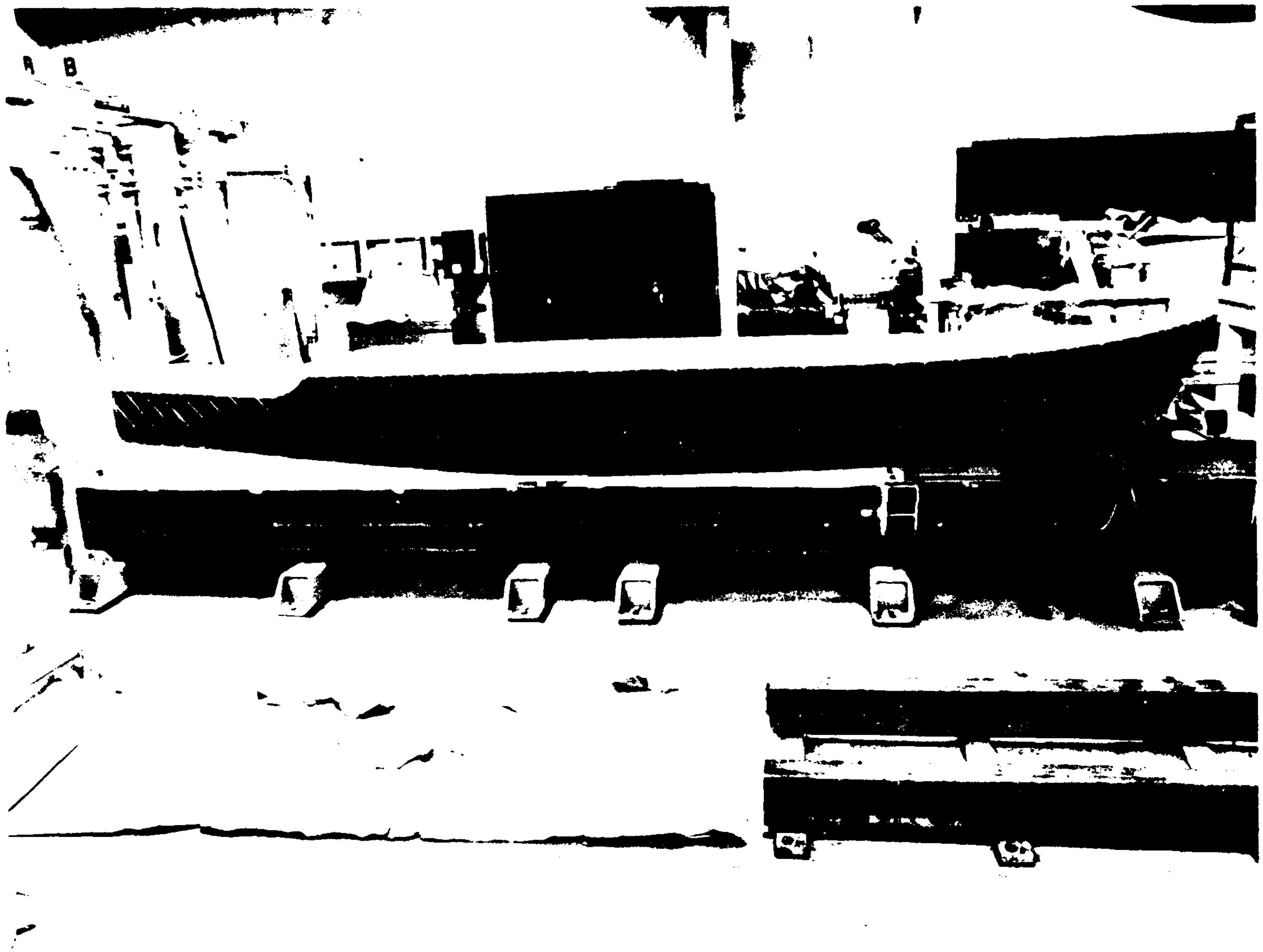


Fig. 4.5 45° Winding Experiments

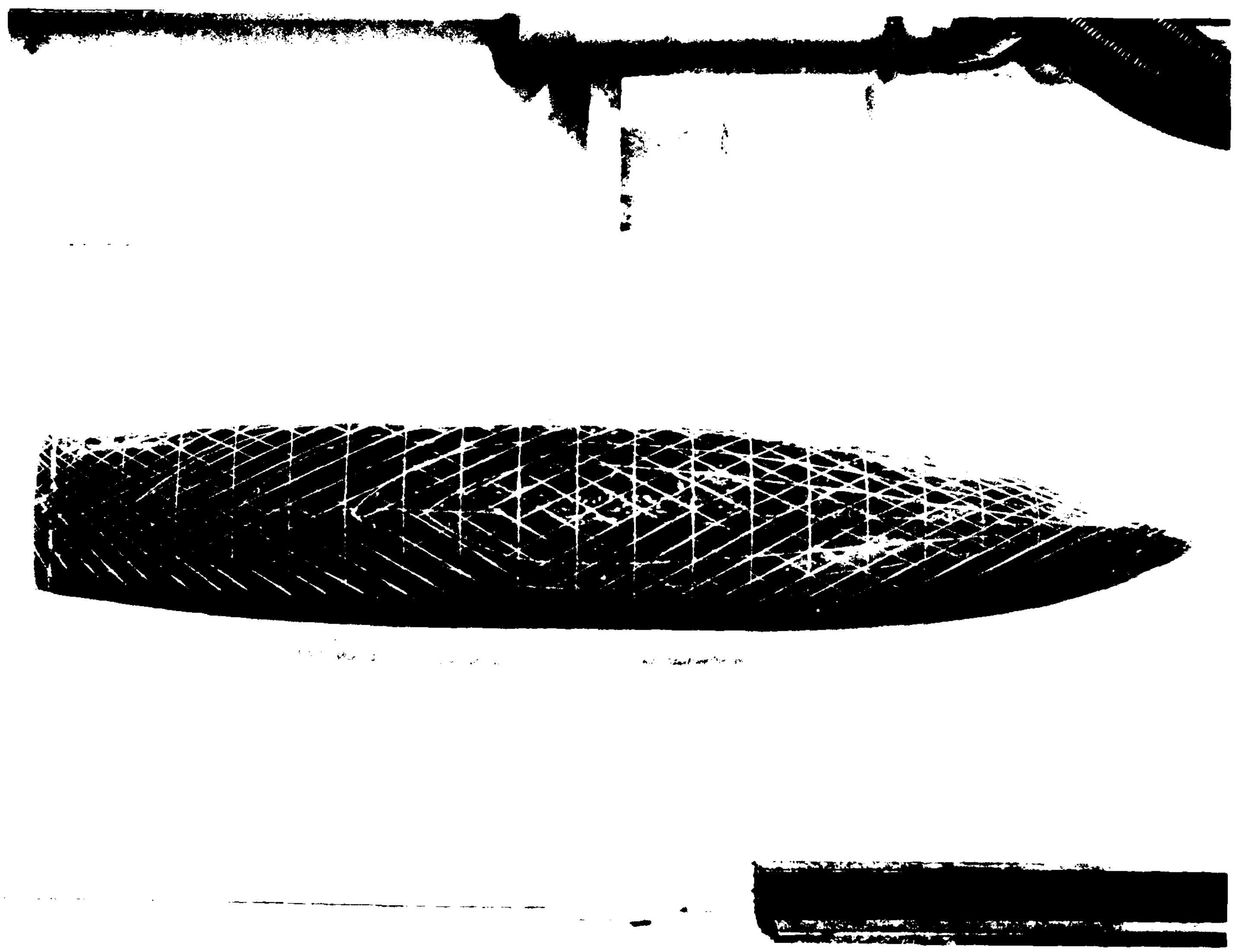


Fig. 4.6. [illegible] Winding Experiments

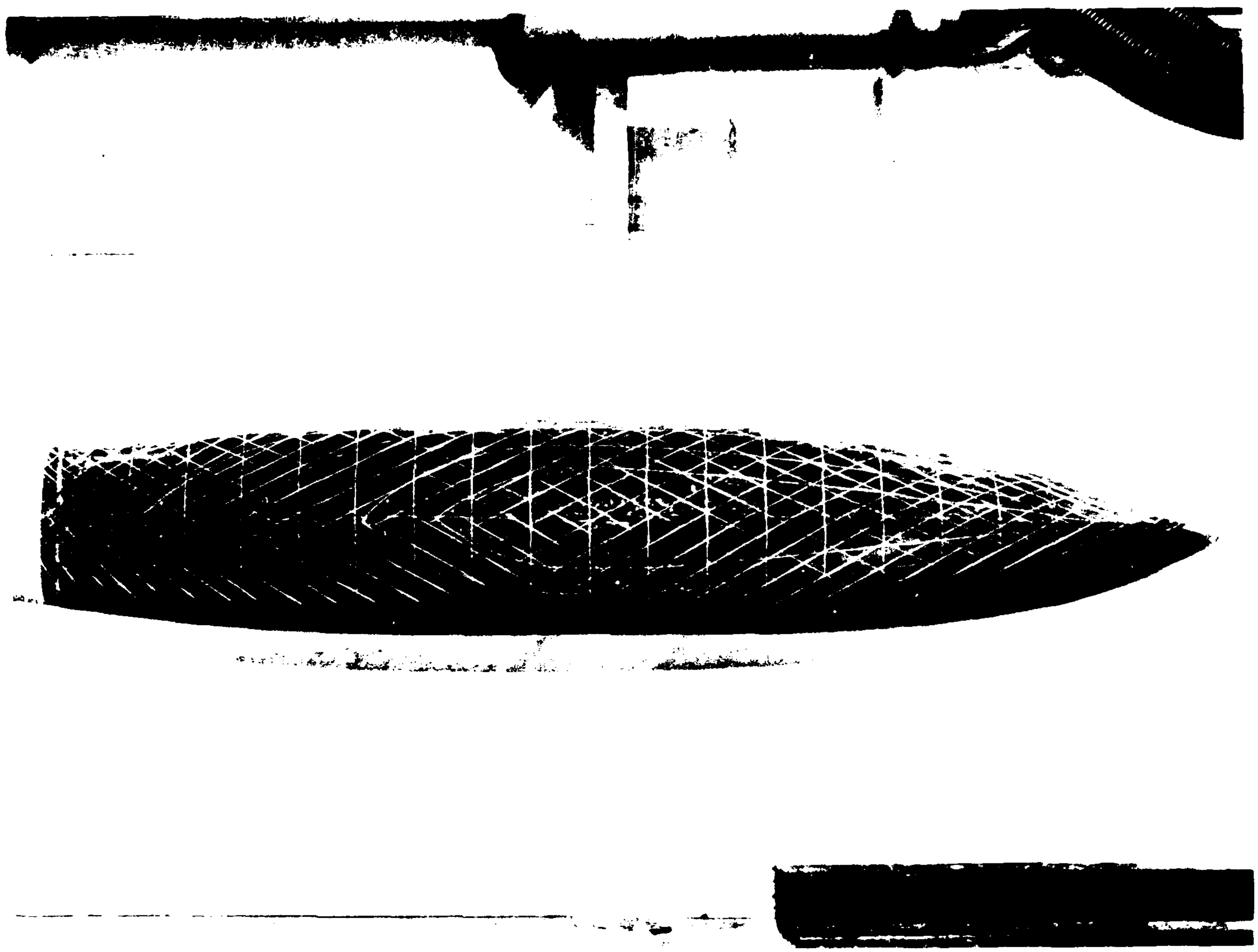


Fig. 4.6 [illegible] Winding Experiments

Fig. 4-7 15° Winding Experiments - Deck View

Fig. 4-8 15° Winding Experiments   Bottom View

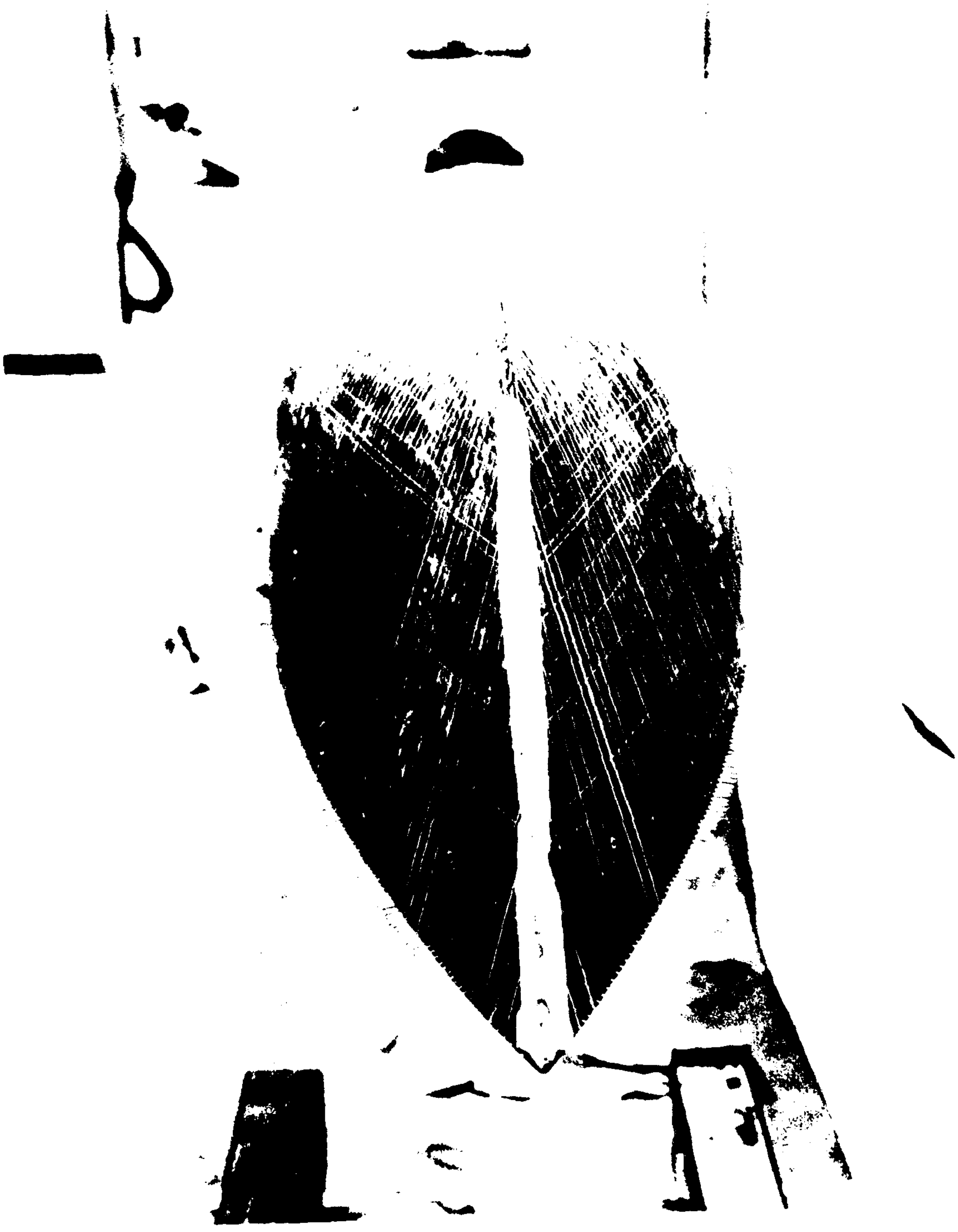


Fig. [illegible] 40° Parallel Bow with [illegible]

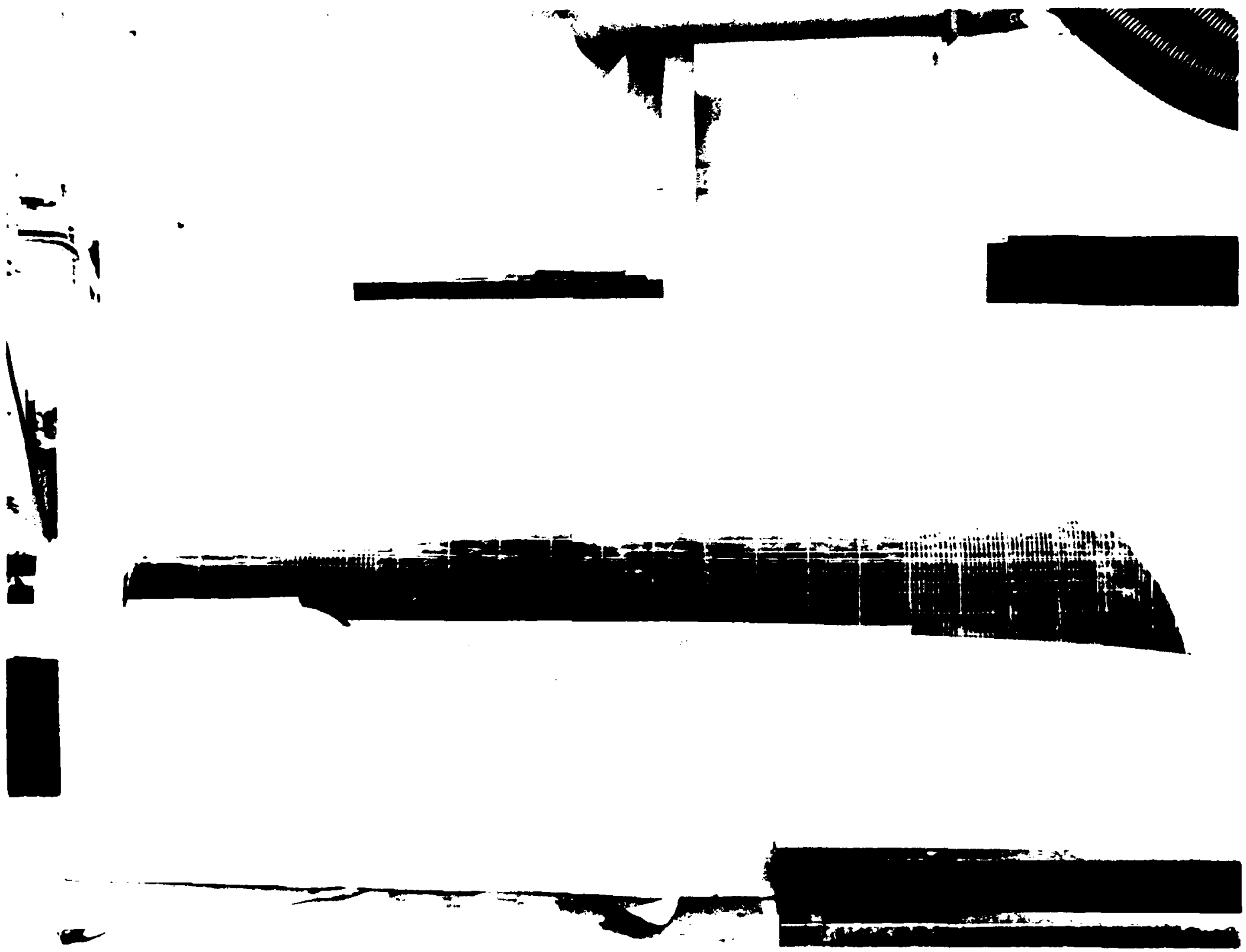


Fig. 4-10 Circumferential (90°) Windings

Fig. 4-11 Bridging at Deck Break, 30° Windings

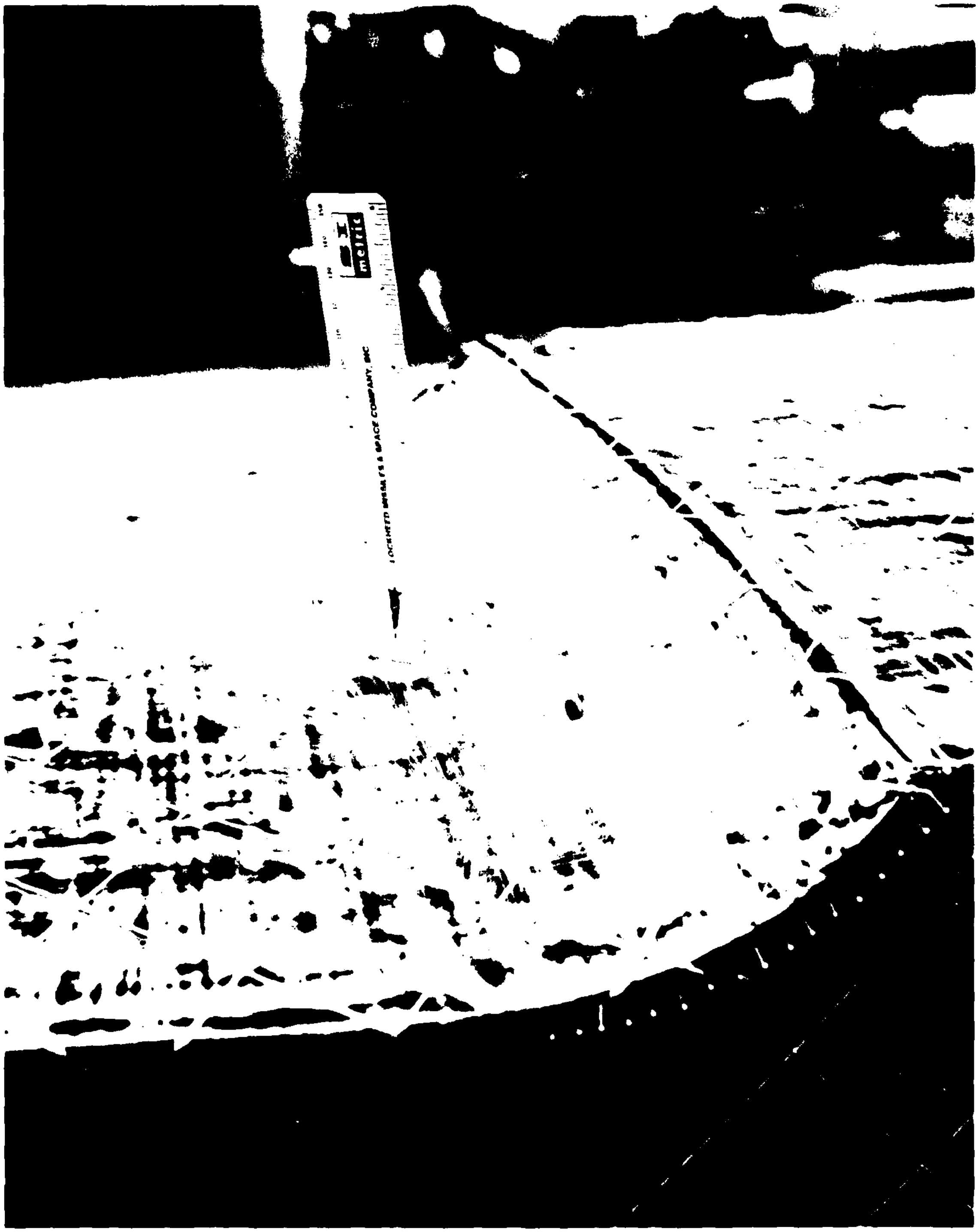


Fig. 4-12 Bridging at Deck Break, 45° Windings

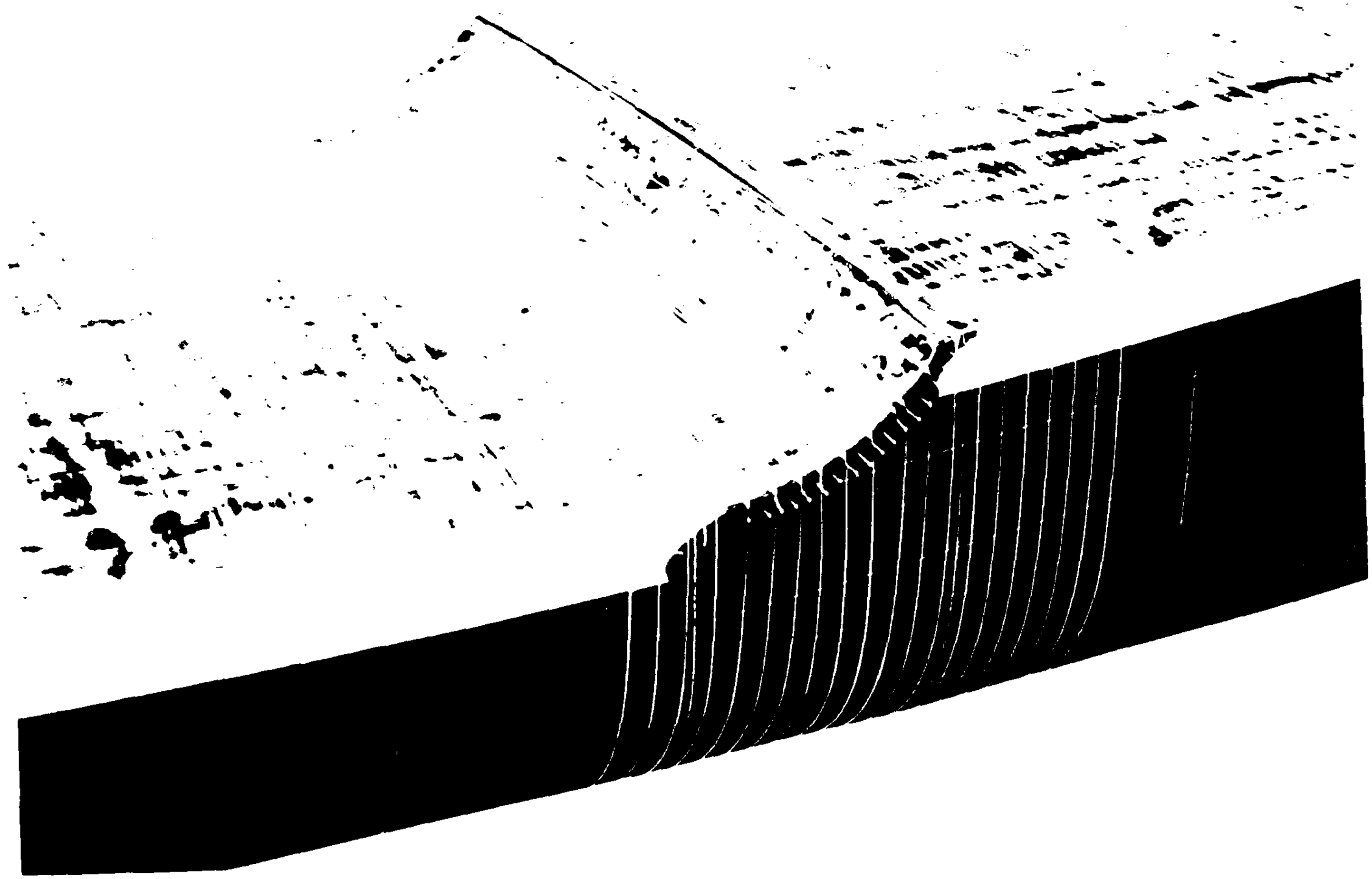


Fig. 4-13 90° Windings at Deck Break

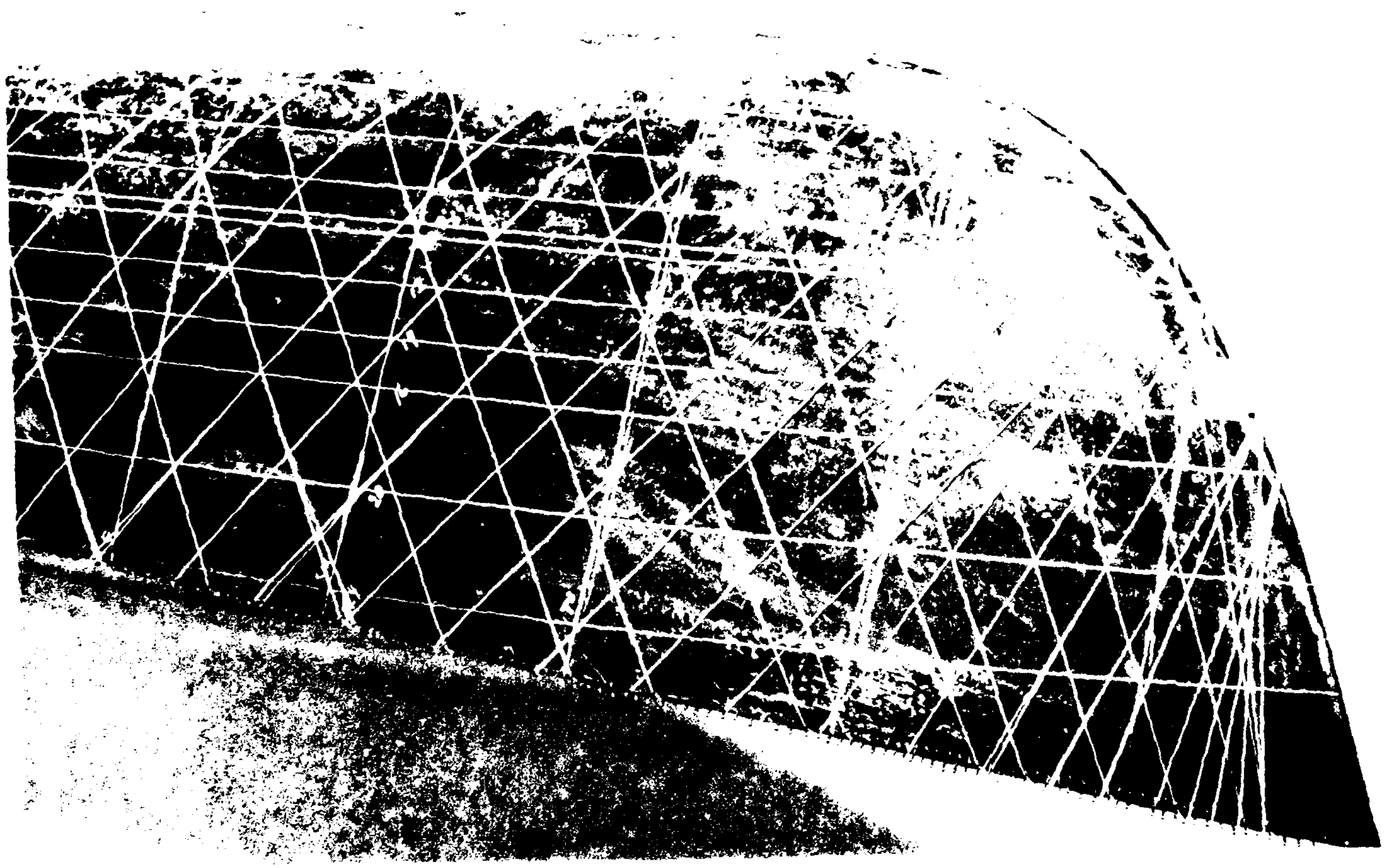


Fig. 4.14 Bow Turnaround [illegible] Winding

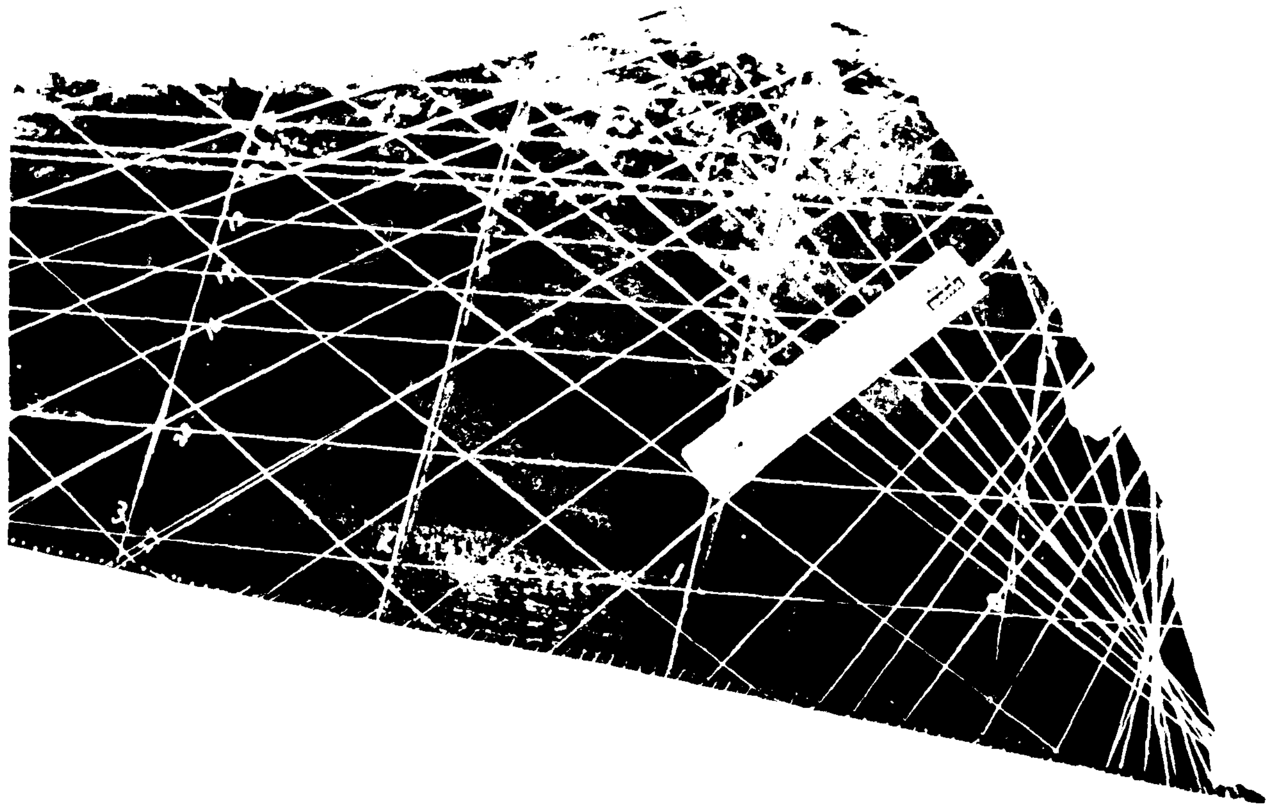
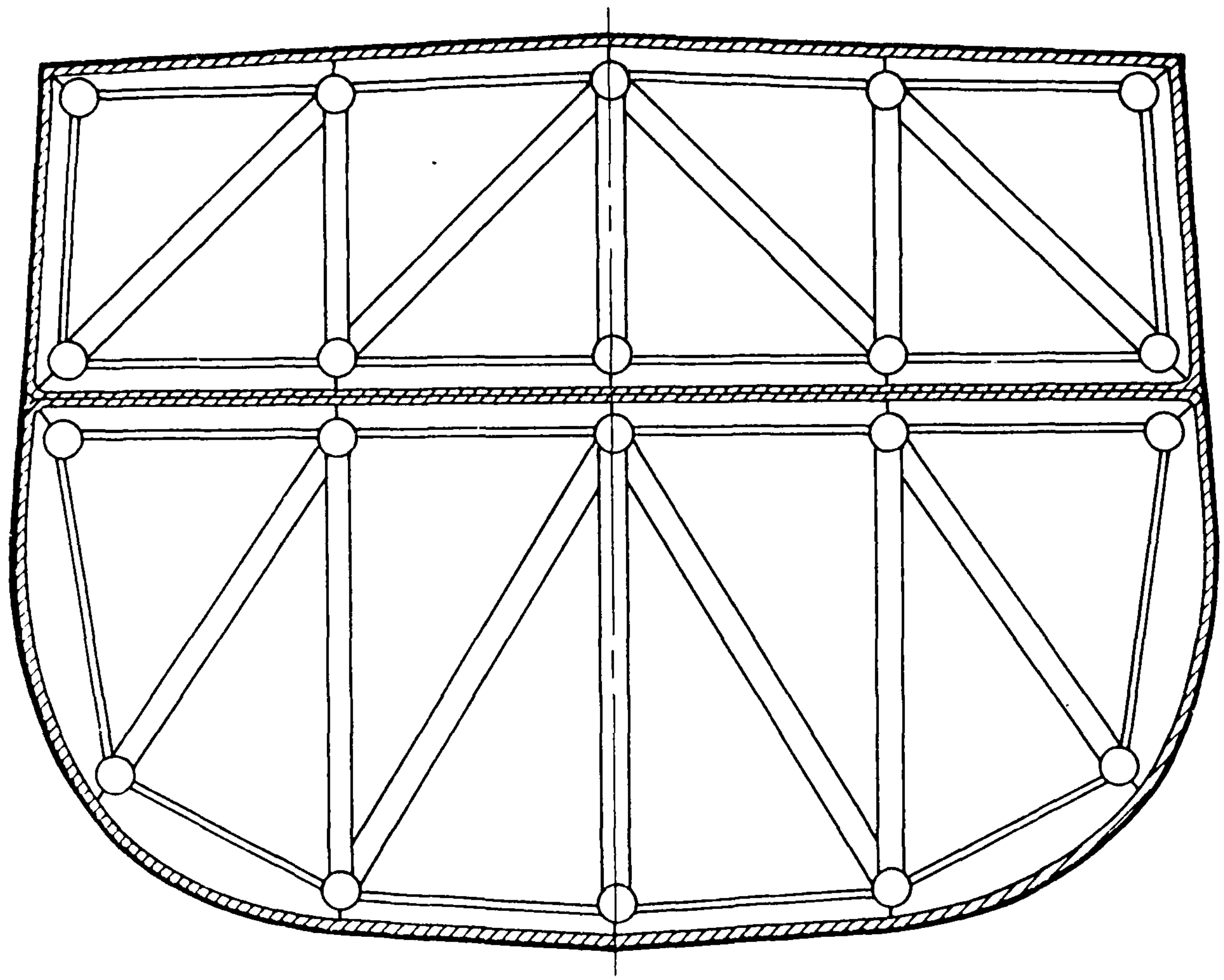
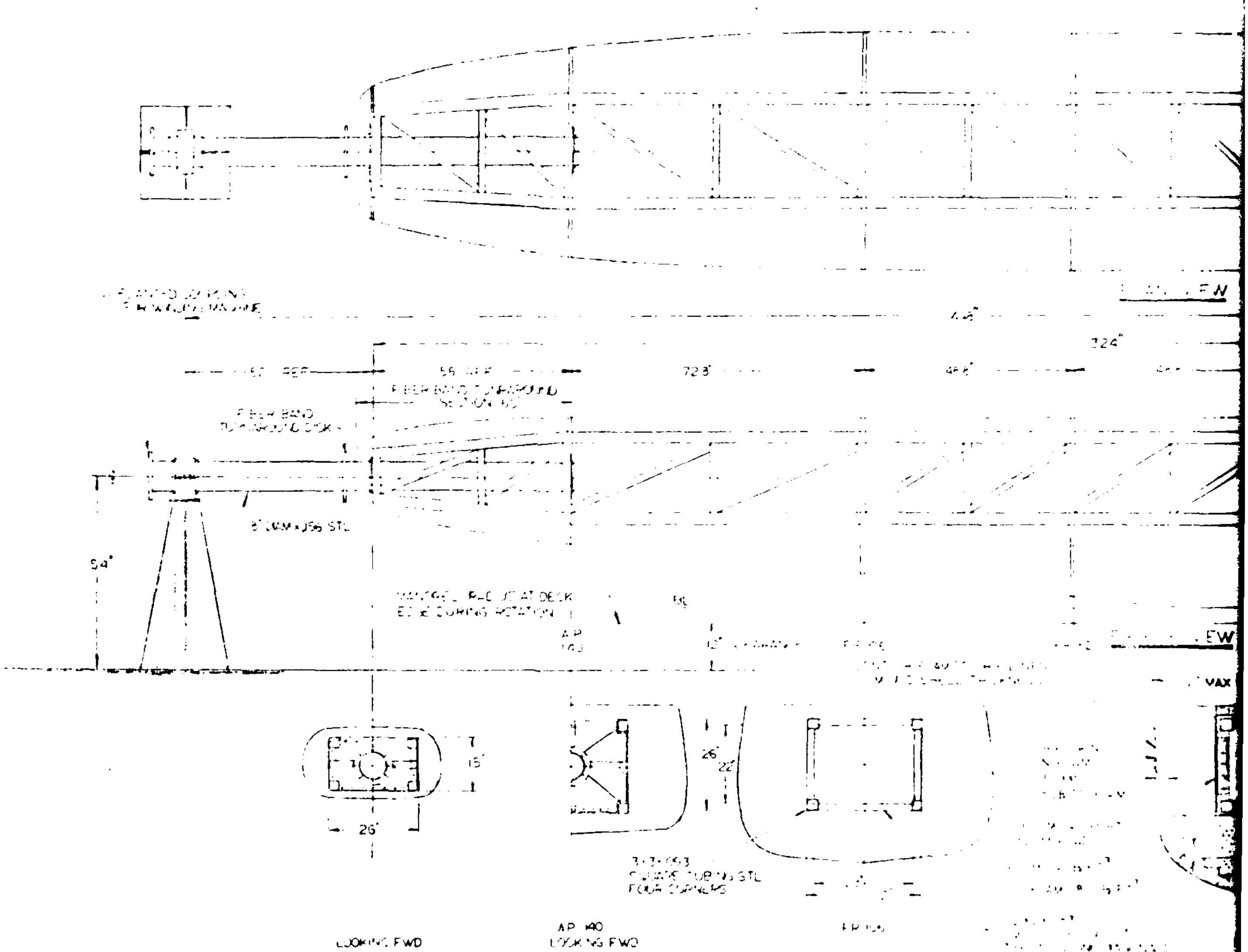


Fig. 4-16 Bow Turnaround - [illegible] Winding

Fig.4-17 Full Scale Truss Structure



TYPICAL FULL SCALE MANDREL



54"
26"
15"
26"
22"
LOOKING FWD
AP 140
LOOKING FWD

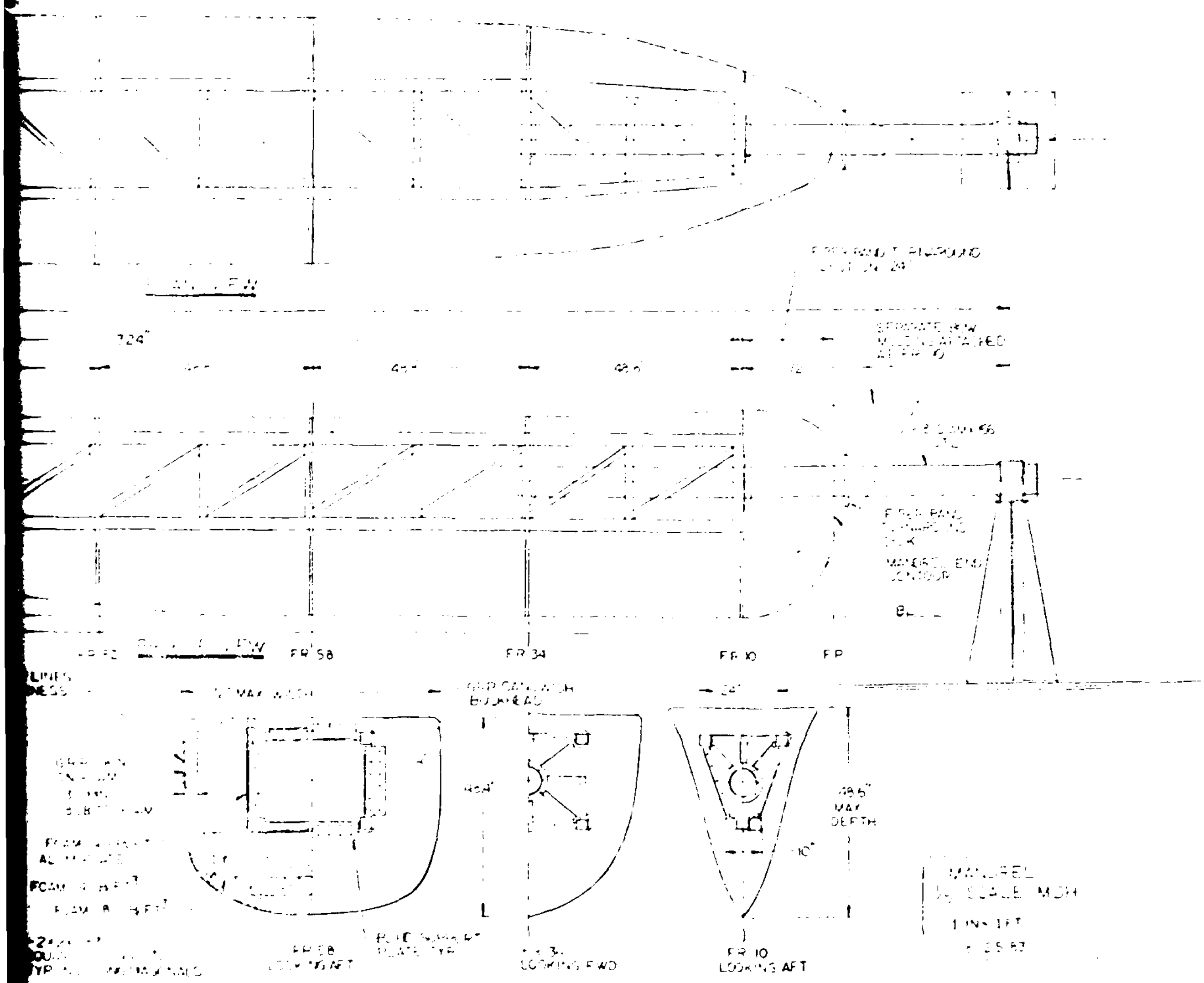
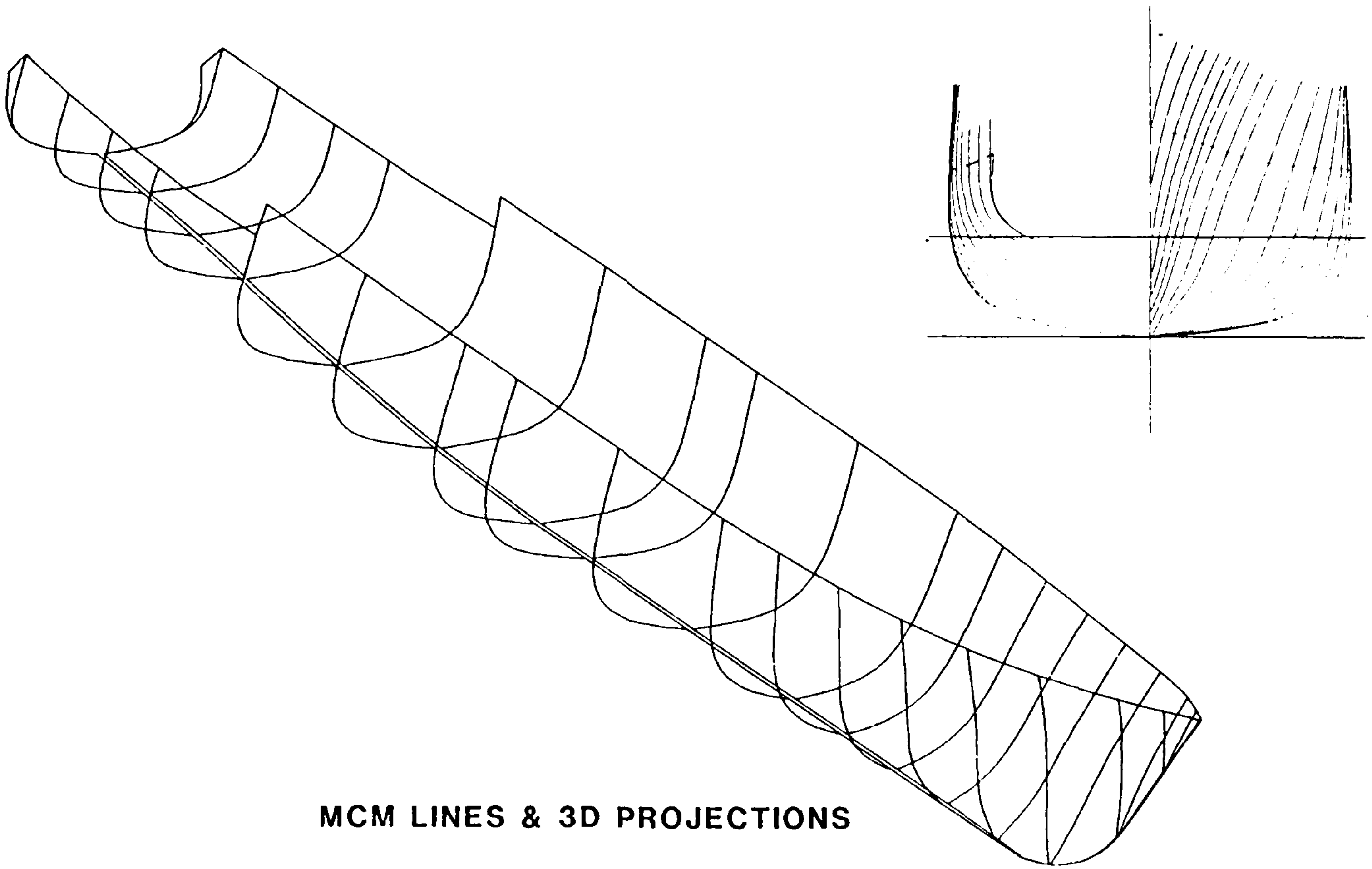


Fig.4-18 Mandrel Preliminary Design - 30 ft Model

Fig. 4.14 Roller Winding Head [illegible]

Fig 4-20 CAD/CAM 3D Lines Drawing for Filament Winding



MCM LINES & 3D PROJECTIONS

SECTION 5
CONCLUSIONS

This section summarizes the conclusions reached during the course of the current study, with regard to the problems inherent in filament winding a large (150-200 ft) ship hull and a 30 ft model of such a hull. Recommended approaches to solving these problems are discussed, along with the analysis, test, and design information which must be developed before a hull can be successfully wound. These conclusions will be discussed in turn for each of the major areas of effort during this study, namely structures, materials, filament winding technology, and winding machine and mandrel development. Section 6 of the report will discuss the program development aspects related to these conclusions.

5.1 STRUCTURE ANALYSIS, DESIGN & TESTING

5.1.1 Structures Analysis

5.1.1.1 Loads Definition. The structural analysis effort for this preliminary phase of the program was limited to simplified panel calculations based on assumed hull bending, UNDEX, and hydrostatic loadings. Before proceeding too far with even a preliminary design of a filament wound hull, better definition is required for the probable critical design loads, which are believed to be local pressure loading due to UNDEX overpressure, and hull bending due to dynamic whipping caused by UNDEX pressure loads.

5.1.1.2 Hull and Laminate Stress Analysis. Before rational selection of fiber paths and layer orientations for a wound ship hull can be made, a better knowledge of resultant combined and

principal stresses is required. The most efficient way to accomplish this is the use of finite element analysis of a model of the major portion of the hull. This was demonstrated using the DIAL computer program during this study. A major benefit of such analysis is that it reveals a more realistic picture of the actual stress distributions in the hull than the classic simplified hull bending and local panel analysis. The results of the finite element analysis allows determination of local fiber stresses by mean of a composite laminate analysis code such as ADVLAM, with a much higher degree of confidence than is possible with the more simplified assumptions of the traditional methods. The results of such a study would be that assumptions of desirable fiberband orientations could be made with a far higher degree of confidence, before related decisions as to manufacturing techniques and approaches have to be made.

5.1.1.3 Materials Data. The analytical tools used for composites in the aerospace industry require more comprehensive three dimensional materials data than is currently available for glass reinforced polyester. Additionally, the different characteristics of filament wound glass materials, with their higher compaction and glass content, is in general not available at all, except for a few proprietary fabrications. When the possibility of mixed reinforcements to achieve better material characteristics is considered, the lack of applicable data is even greater. Thus, before any reliable structural design projections for a filament wound hull can be made, at least a minimal materials data base must be developed by fabrication and testing of the relevant laminate samples.

5.1.1.4 Model Analysis. The final conclusion regarding the structures analysis area is that although the work done in this phase is considered to be adequate for identification of the general scantlings of a 150 ft minesweeper, for purposes of

scaling to model size, the limitations of the analysis must be recognized. The result is that these findings should not be projected to discussion of a full size ship without careful qualification, based on the limitations of the assumptions and procedures.

5.1.2 Structures Design

It should first be noted that the proposed model design is based on geometric scaling of ship scantlings from a rather simplified (and from a ship design point of view) analysis. Therefore, it is necessary to carefully review the purposes of the proposed model before proceeding with construction, in order that final model scantlings and manufacturing procedures can be based on the appropriate criteria.

A key requirement in this regard is that the model construction should allow for the development and inclusion of several bulkhead and deck to hull joint designs. This will allow the maximum amount of information on this subject to be developed within the required funding constraints of the next phase.

5.1.3 Structural Testing

Several conclusions can be reached regarding testing of filament wound hull laminate and joint samples. The first is that sample panels and joints can be tested for structural characteristics and performance without exact knowledge of full scale loads and stresses. This means that this part of the overall effort can be started before detailed structural analysis has been performed.

The second point is that due to the shear and directional characteristics of the filament wound materials, tests must be very carefully designed to apply loads in a realistic manner which

does not precipitate premature or unrealistic failure modes.

Finally, it is reiterated that better 3-D data on the materials of interest, produced by filament winding of panels with full scale curvature, is needed as a first priority to structural analysis or design of joints.

5.2 MATERIALS

5.2.1 *Reinforcements*

The first conclusion with regard to reinforcements is that adequate information is available for E Glass, S-2 Glass, carbon, and Kevlar, but not on combinations of these with the resins of interest.

5.2.2 Resin Systems

Better resins data is needed on the characteristics of toughened isophthalic polyesters, vinyl esters (with and without toughening), and particularly on quick "B-stage" or tacky state cure cycles to assist in holding fibers as placed. Much of this information will have to be developed from experiments in the early stages of winding the 30 foot model, or using smaller laminate samples. All of this information must be developed for "thick" sections, to relate them to the objective ship structure, and thus some of the experimentation should perhaps involve sections thicker than the scaled model scantlings.

5.2.3 Laminates

Since the real objective is the structural matrix of reinforcements and resin, material characteristics and performance data should be developed on test sections which have adequate

relationship to full scale, using the resin systems and cure cycles of interest. This data should include the reinforcements of interest, both alone and in combination. The British have demonstrated these combinations, such as glass and carbon,to have potential synergistic benefits.

5.3 FILAMENT WINDING TECHNOLOGY

5.3.1 Feasibility

The basic winding work done in this phase demonstrates the general feasibility of using filament winding techniques to apply resinated glass fibers to a ship shaped mandrel. The successful demonstration of this capability is dependent, however, on the development of certain advanced winding techniques to resist fiberband slippage, bridging, and sagging. Proposed methods for accomplishing this have been discussed, but must be developed in the shop and laboratory during the preparatory phases of the model construction program.

5.3.2 Structural Efficiency

Due to the similar shape problems in a full scale ship and large model such as the one proposed, the necessary winding techniques and resultant structure can be adequately demonstrated at model scale. One exception to this is the issue of laminate thickness and its effect on cure. As mentioned previously, it may be desirable to increase the thickness in portions of the model, or on a special mandrel, to reproduce the order of magnitude thickness of an actual ship hull.

5.3.3 Cost

Assuming that the reference winding techniques can be successfully developed, a critical question will be the relative cost of filament winding versus hand layup. The British MOD(N) experience has shown that approximately 80% of the hull fabrication cost is in labor. It will be necessary to establish how the elimination of a large fraction of this labor compares to amortization of machine, mandrel, and other facility costs. Additional considerations, such as elapsed fabrication time and surge capability, should also be addressed.

5.4 MACHINE & MANDREL DEVELOPMENT

5.4.1 Current Machine Technology

The currently available rotating axis winders, such as Lockheed's McClean-Anderson W-60 machine or those used by Thiokol and Hercules for missile body winding, are adequate for the winding of a 30 foot model, assuming certain modifications. The cost of these modifications, having to do with winding head movement and control, has been estimated. No ring type winder which is capable of winding around a mandrel the size of a 30 foot ship model is currently known to exist. It is possible that extensive modifications to a winder such as the M-A machine could be made to provide a ring winding capability. This alternative is currently being evaluated.

5.4.2 Ring Winding Machine Technology

Since no ring winder currently exists in a size compatible with the projected 30 ft model, the preliminary design of such a machine would be a prerequisite to estimating machine construction costs. In order to do such a design, the basic configuration

of a full ship scale ring winder would have to be established if the smaller machine was to be representative of the full scale approach.

5.4.3 Full Scale Winder Design

The foregoing discussion suggests that the first step in addressing the machine design problem would be to perform a concept or preliminary design of both a ring winder and rotating axis winder capable of handling a 200 foot hull. This study must of necessity include consideration of the design and cost of the mandrels as well as the machines, since the simpler fixed mandrel of the ring winder is a tradeoff with the more complex machine design, when compared to conventional rotating axis machines.

Because the question of full scale machine design and winding concept feasibility are closely interelated, this subject should be carefully reviewed before proceeding with the next phase of the filament winding program.

SECTION 6
RECOMMENDATIONS

This section will discuss the program development necessary for responding to the conclusions presented in the previous section, and the specific recommendations for program actions relating to these conclusions.

6.1 PROGRAM DEVELOPMENT

In order to define an orderly and cost effective program to proceed with the development of a filament wound ship hull, Lockheed Advanced Marine Systems has begun to identify the specific tasks, schedules, and efforts necessary to accomplish the program goals of demonstrating the feasibility of winding ship hulls by means of winding a 1/5 scale model of an MSH, and then proceeding with the other tasks necessary to develop the technology for successfully winding a full scale ship.

A preliminary task statement for the overall program showing the major steps necessary to achieve the successful winding of a ship hull has been prepared. On the assumption of a maximum near-term effort proceeding toward both the model and ship goals, another task statement has been prepared for next year, at a more detailed level. As these plans are not part of the contract work statement and effort, they will be transmitted separately from this report, and after discussion with the Navy modified as required. The planning that has been accomplished to date, however, along with the material and winding investigations already discussed, allow certain preliminary conclusions about the probable content and priorities of such a ship winding developement program.

First, based on the results of the study, and discussions with cognizant Navy personnel, the following technical objectives are assumed to be appropriate for preliminary program planning purposes. They are listed in the general order of currently perceived importance, at least from a schedule point of view:

(a) Demonstrate the winding of a ship hull shape by means of the 1/5 scale model.

(b) Demonstrate the (subscale) feasibility of at least one viable winding machine concept, again by means of the 1/5 scale model.

(c) Demonstrate acceptable achieved filament wound material characteristics, either by means of testing coupons of the 30 foot hull, or by fabricating and testing sample specimens under winding conditions closely approximating those of the 30 foot model and/or the full scale ship.

(d) Demonstrate the design and fabrication of acceptable critical joints, including those between the hull, bulkheads, decks, transom, bow module, foundations, and structural stiffeners or other reinforcements. This should be accomplished in a preliminary way on the model hull, and then to full or quasi-full scale on special joint samples produced in shop conditions and tested to failure. They may of be proceeded by subscale model fabrication and test where deemed appropriate.

(e) Analysis and demonstration of outfitting procedures and access provisions. Because of the closed nature of a monocoque hull/deck winding, and the large portion of a ships total labor cost contained in the machinery,

piping, electrical, and outfitting tasks, it will be necessary to demonstrate that the complication of this effort does not result in labor cost increases that overwhelm the savings in labor available by the utilization of automatic filament winding procedures. These projections should also include the pro-rated mandrel and special handling equipment costs, and the appropriate facility and/or amortization costs associated with a large winding facility and machine. These items should also be compared with the comparable costs for a hand layup facility such as used by the British and Europeans, or proposed by the selected contractor for the conventional (hopefully GRP) MSH design.

(f) Finally, the results of the above efforts should be combined in a cost study which defines the basis for any cost savings in the filament wound approach to a GRP minesweeper, or if it is attractive for other reasons such as surge production capability, any cost implications associated with such a capability.

6.2 RECOMMENDATIONS

Based on the above defined tasks and review of the contract results, the following recommendations are made for near term actions to advance the state of the overall effort to develop the technology for filament winding of 100-200 foot ship hulls.

(a) The specific objectives of the next phase should be carefully reviewed in light of the results of this study and the overall program objectives, to establish priorities for the specific task areas identified in the previous two sections of this report.

(b) An overall program plan and projected funding profile

should be developed to allow adequate Government and contractor planning in terms of funding, manpower, and schedule objectives and commitments. This will be an ongoing task subject to periodic review and adjustment, but it should be started.

(c) Long range materials and laminate studies and tests should be begun as soon as possible, in order that necessary information for design is available as required. The current study effort has already been somewhat hampered by the lack of such information.

(d) Design studies of a full scale winding machine should be started in order to provide the cost information necessary for planning, and to allow fabrication of the 30 foot model on a machine configuration which will demonstrate the feasibility of the projected full scale machine and winding approach. This task involves developing the information necessary to justify a rational choice between a rotating mandrel approach, with its simpler machine and more complex mandrel, and the ring-winder approach with its more complex machine and simpler static mandrel.

(e) Finally, it is recommended that a current Navy program producing GRP boats in the 40 to 60 foot size range be identified, and a program developed to filament wind a demonstration version of such a hull. Hopefully, such a hull could be outfitted by the manufacturer of the hand layup production version, and its performance and cost effectiveness be demonstrated in actual service. This would provide an int -im step before proceeding to the more demanding and costly construction of a ship hull such as an MSH.

(f) As a corallary to the previous recommendation, an evaluation of the relative merits of producing a 1/5 scale minesweeper hull versus a full scale Navy boat hull should be made. It is possible that a more cost effective and lower risk program could be developed around an approach involving quasi-full boat scale experiments on a simple midship section mandrel to develope resin formulations and winding techniques, followed by the production of a full scale boat hull for outfitting and service, or a subscale ship hull for structural or UNDEX testing.

APPENDIX A

Local Winding Angles for Helical Winding Pattern

Base Angle at Amidships

1/20 SCALE Ships Hull

Winding Angles

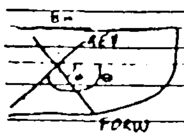
SKIN EXPANSION

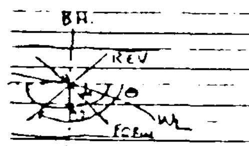
STARBOARD SIDE (RIGHT)

F = α R = θ

F = α R = θ

THE ANGLES RECORDED ARE PARALLEL WITH THE LINK HEADS BEING THE REFERENCE LINES





Station Line → / Water Line ↓ WL		-1	-1/2	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20		
24	F				60	42	41	41	43	45	43	50	50	50	50	50	50	[illegible]	50	50					F	24
	R				139	136	135	135	134	132	130	130	130	[illegible]	131	131	131	[illegible]	131	132					R	
20	F				50	41	40	41	43	45	43	50	50	50	50	50	50	[illegible]	50	50	50	47	47	50	F	20
	R				139	138	135	135	134	133	130	130	130	[illegible]	131	131	131	[illegible]	131	133	135	124	124	129	R	
MD																										
16	F				45	41	40	41	43	44	46	50	50	50	50	50	50	49	50	50	50	47	47	50	F	16
	R				132	138	136	135	134	133	132	130	130	131	131	131	131	130	133	135	135	132	134	[illegible]	R	
14	F				41	41	40	41	43	44	46	50	50	50	50	50	50	49	50	49	48	46	47	50	F	14
	R				138	132	136	135	134	133	132	131	130	131	131	131	131	130	133	126	127	132	131	[illegible]	R	
12	F				41	41	43	42	43	44	46	50	50	50	50	50	50	49	50	48	45	46	47	46	F	12
	R				135	132	139	135	134	133	132	131	130	131	131	131	131	133	133	136	132	132	134	135	R	
10	F				41	41	43	43	43	[illegible]	43	50	50	50	50	50	50	48	50	46	46	43	42	[illegible]	F	10
	R				135	140	139	132	134	133	137	131	132	131	131	131	131	133	135	137	132	139	133	[illegible]	R	
8	F				41	43	44	42	45	44	43	47	[illegible]	50	49	50	47	49	46	45	46	43	42	[illegible]	F	8
	R				135	140	140	138	138	135	137	131	131	131	130	131	134	133	135	136	132	136	132	126	R	
6	F				42	43	44	42	45	44	47	47	48	48	49	50	47	47	44	43	43	42			F	6
	R				132	140	140	136	136	[illegible]	135	131	131	131	130	131	134	134	[illegible]	136	140	140			R	
4	F				42	44	47	42	[illegible]	47	47	46	48	48	47	46	47	47	41	43					F	4
	R				130	140	140	141	140	[illegible]	135	133	131	131	124	124	134	137	140	128					R	
2	F				42	44	44	43	45	47	45	46	46	45	47	46	47	43							F	2
	R				125	140	142	141	140	140	[illegible]	133	135	134	134	134	134	137							R	
1	F					44	47	43	45	44	45	46	46	45	47	47	[illegible]								F	1
	R					140	140	141	140	140	126	132	136	131	134	126	132								R	
MD CL																										
01 CL																										

* 95.4 % OF ALL RECORDED STATIONS ARE WITHIN 45° ± 5°

1/20 Scale Ships Hull

Winding Angles

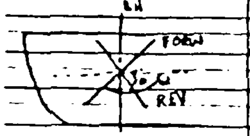
Skin Expansion

LOCKHEED #37-LE-45-L-0

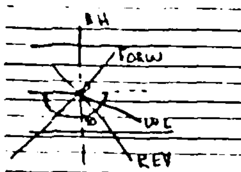
SKYWIND KEVLAR 49-1140 LENIER

Station Line →
Water Line ↓

PORT SIDE (LEFT)



R:θ F:α



R=θ F=α

ANGLES RECORDED [illegible]

WL		-1	-½	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20		
24	R			44	42	43	45	48	48	47	48	49	51	50	50	50	49	50	49	48					R	31
	F			88	127	13[illegible]	140	140	138	[illegible]	134	131	132	131	1[illegible]3	131	131	131	131	131					F	
20	R			53	42	43	45	45	48	[illegible]	47	49	51	50	[illegible]	50	49	50	49	48	47	44	46	53	R	30
	F			83	127	137	140	139	138	[illegible]	134	131	132	131	130	131	131	131	131	131	133	133	134	130	F	
MD																										
16	R				43	42	45	45	47	47	49	49	49	49	50	50	49	50	49	43	47	49	46	50	R	16
	F				137	140	140	138	137	134	134	131	131	131	130	131	131	131	131	132	133	133	134	133	F	
14	R				43	41	43	45	47	47	49	49	49	47	50	50	50	51	49	[illegible]	[illegible]	44	46	50	R	14
	F				137	140	138	138	137	134	134	131	131	131	130	131	130	132	131	133	133	133	134	13[illegible]	F	
12	R				46	41	43	45	47	47	49	49	[illegible]	47	50	[illegible]	50	50	42	43	[illegible]	46	46	[illegible]	R	12
	F				138	140	138	138	137	136	134	131	131	131	130	13[illegible]	130	133	131	132	[illegible]	134	132	[illegible]	F	
10	R				46	41	41	42	47	47	49	[illegible]	[illegible]	47	47	[illegible]	50	50	47	47	47	[illegible]	47	[illegible]	R	10
	F				138	140	138	136	136	136	134	131	131	131	131	133	130	133	[illegible]	135	13[illegible]	137	137	[illegible]	F	
8	R				47	39	41	42	44	47	40	48	47	49	51	48	50	50	48	47	43	45	47	[illegible]	R	8
	F				140	140	138	136	136	136	133	132	[illegible]	131	131	13[illegible]	132	131	131	[illegible]	121	129	137	140	F	
6	R				47	39	41	42	44	44	46	48	46	47	49	[illegible]	47	46	44	43					R	6
	F				140	138	138	136	136	136	133	132	133	134	131	132	135	132	13[illegible]	137					F	
4	R				50	40	39	40	45	44	46	48	48	47	47	[illegible]	47	46	44	43					R	4
	F				140	138	137	135	137	136	133	132	133	134	134	13[illegible]	132	132	134	137					F	
2	R				50	41	39	40	43	43	45	45	46	47	47	45	45	45							R	2
	F				140	140	137	135	137	137	136	135	134	134	134	135	134	136							F	
1	R						40	36	41	43	45	[illegible]	46	45	45	45	45								R	1
	F						140	137	138	138	136	135	134	135	135	[illegible]	135								F	
MD CL																										
BT CL																										

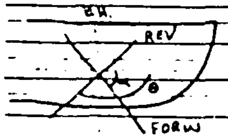
93.3% WITHIN ±5° AT 45°

1/20 Scale Ships Hull — SAC WIND-KEVLAR 49-1..

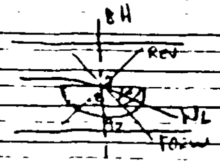
Winding Angles — PROGRAM 24-PE-45° L..

Skin Expansion

Station Line →
Water Line ↓
Starboard Side (Right)



R=θ F=α



WL		-1	-1/2	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20		
24	F			110	64	41	31	37	35	35	38	40	43	45	45	48	48	46	48	45					F	24
	R			145	145	143	142	141	138	138	[illegible]	135	135	135	135	138	138	139	139	139					R	
20	F			[illegible]	47	35	35	32	[illegible]	35	[illegible]	45	43	45	43	48	48	46	48	45	45	44	43	42	F	20
	R			128	145	[illegible]	143	140	[illegible]	132	[illegible]	135	135	135	135	138	138	138	139	139	142	140	136	130	R	
MD																										
16	F				35	33	33	35	35	35	39	41	43	45	45	46	47	47	47	45	45	44	42	42	F	16
	R				143	146	144	141	138	138	136	135	135	135	135	136	136	139	139	139	142	140	137	130	R	
14	F				39	33	33	35	35	35	39	41	43	45	45	46	41	47	41	45	43	44	42	42	F	14
	R				143	146	144	141	139	138	136	135	135	135	135	136	136	139	139	139	142	140	137	129	R	
12	F				31	33	39	35	34	35	39	41	43	45	45	46	47	46	47	[illegible]	45	44	42	42	F	12
	R				140	146	144	141	139	138	137	136	136	135	135	136	137	137	139	142	142	140	137	129	R	
10	F				31	37	34	35	36	37	31	41	43	45	45	45	47	46	45	[illegible]	45	42	40	42	F	10
	R				136	147	144	143	140	[illegible]	137	136	136	135	135	[illegible]	137	137	140	142	142	141	135	135	R	
8	F				34	35	37	35	37	[illegible]	39	41	43	45	45	45	45	45	45	43	43	42	41	42	F	8
	R				130	145	146	143	140	[illegible]	137	130	136	135	135	[illegible]	140	140	140	142	142	141	137	130	R	
6	F				32	35	29	36	37	37	39	38	41	45	45	45	45	45	44	44	43	42			F	6
	R				130	145	146	143	140	140	[illegible]	137	136	135	135	137	140	140	141	142	142	141			R	
4	F				32	33	38	36	37	37	39	37	41	43	47	45	45	44	44	43					F	4
	R				130	140	141	143	[illegible]	[illegible]	138	137	136	136	137	138	140	140	141	142					R	
2	F					35	37	29	38	36	39	41	41	42	44	44	45	44							F	2
	R					140	148	149	140	[illegible]	138	138	138	137	137	138	142	140							R	
1	F					35	35	37	37	[illegible]	43	42	41	43	44	[illegible]	44								F	1
	R					144	143	149	140	[illegible]	[illegible]	137	137	137	137	[illegible]	137								R	
MD CL																										
DT CL																										

A-3

50 76% within ±5° at 45°

1/20 Scale Ships Hull

DRY WIND - KEVLAR 49 - 11% [illegible]

Winding Angles

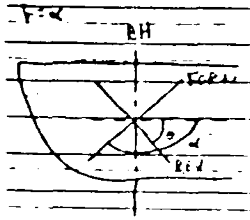
Skin Expansion

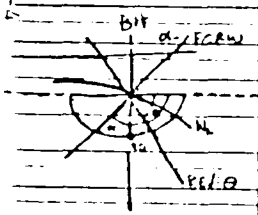
Station Line → / Water Line ↓

PORT SIDE

(LEFT)

FIG





SH		-1	-1/2	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20		
24	R				37	37	38	40	44	44	45	45	46	45	45	44	43	41	41	40					R	24
	F				135	143	147	147	146	146	142	141	140	137	135	134	134	134	134	135					F	
20	R				38	37	36	40	44	44	45	45	46	45	45	44	43	41	41	40	40	40	44	50	R	20
	F				138	146	146	147	146	146	145	141	140	137	135	134	134	134	134	135	136	[illegible]	139	138	F	
MD																										
16	R				37	37	39	41	42	42	44	45	46	45	45	44	43	41	41	40	40	40	44	48	R	16
	F				144	147	147	145	146	145	145	141	140	137	135	134	134	134	134	135	136	137	134	138	F	
14	R				40	37	39	40	40	42	44	45	41	45	45	45	43	41	41	40	40	40	44	46	R	14
	F				148	147	147	145	146	145	145	141	138	137	135	136	134	134	134	135	136	137	134	138	F	
12	R				44	34	37	40	39	42	44	45	44	45	45	45	43	41	41	39	40	40	44	50	R	12
	F				146	147	147	147	146	144	144	141	138	137	135	135	134	134	131	138	139	139	140	138	F	
10	R				44	33	36	34	39	42	44	45	44	45	45	45	43	41	41	39	37	40	44	53	R	10
	F				147	146	144	147	140	144	144	141	138	137	137	135	134	134	137	138	139	139	140	138	F	
8	R				50	37	36	34	42	40	42	45	44	45	45	44	42	41	41	38	39	[illegible]	44	50	R	8
	F				146	148	145	145	140	142	140	141	138	137	137	136	136	136	137	139	139	139	138	138	F	
6	R				54	35	36	38	42	40	42	45	44	45	45	43	42	40	38	38	37	40			R	6
	F				149	145	145	145	140	142	140	140	139	137	137	137	[illegible]	136	138	139	139	139			F	
4	R				57	40	30	38	40	41	41	43	44	44	45	44	41	40	40	39					R	4
	F				148	144	144	144	143	142	140	140	139	139	137	137	136	136	136	136					F	
2	R					43	39	40	43	44	45	44	44	44	43	44	41	41							R	2
	F					145	144	145	144	143	141	140	139	139	137	137	137	136							F	
1	R					43	36	40	43	44	45	44	44	44	41	44	44								R	1
	F					145	146	145	144	143	141	140	139	139	137	137	137								F	
MD CL																										
OT CL																										

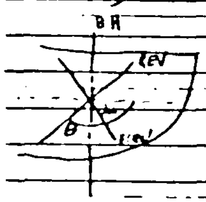
- The angles recorded are taken with the [illegible] being the reference plane.

1K N/D - KEVLAR 49 - 1140 LEA...
PROGRAM 33 - PE: 30°

Winding Angles 6-9-83 (THURSDAY)

Skin Expansion

STARBOARD SIDE (RIGHT)



Station Line → / Water Line ↓		-1	-½	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20		
24	F			69	15	19	19	19	20	22	25	25	25	25	27	26	30	31	32	31					F	24
	R			142	154	157	155	153	155	152	150	150	150	151	152	153	152	152	153	151					R	
20	F			69	19	15	15	16	20	22	22	25	25	25	27	26	30	31	32	31	32	30	31	31	F	20
	R			142	150	158	157	153	153	152	150	150	150	151	151	153	152	153	153	151	152	150	148	146	R	
AD																										
16	F				13	15	18	18	22	25	25	25	25	25	28	30	31	31	31	31	32	30	31	33	F	16
	R				142	153	158	153	153	152	150	150	150	151	151	151	152	152	152	153	152	152	148	145	R	
14	F				18	17	18	22	22	25	24	25	25	25	28	30	31	31	31	31	32	30	30	33	F	14
	R				138	151	152	153	153	152	151	150	150	151	151	151	152	151	152	152	152	152	147	14[illegible]	R	
12	F				18	17	19	22	23	24	24	25	25	25	28	30	31	31	30	30	28	30	30	33	F	12
	R				158	149	152	153	154	155	151	150	152	152	151	151	153	153	152	152	152	152	147	141	R	
10	F				18	21	19	24	23	24	24	25	25	25	29	30	31	31	30	28	28	28	30	33	F	10
	R				133	147	154	158	154	155	151	150	151	150	151	151	153	152	152	154	[illegible]	150	145	141	R	
8	F				21	21	26	22	23	24	24	25	26	25	28	30	30	31	30	28	27	28	30	32	F	8
	R				132	141	154	158	155	155	151	150	151	151	151	153	153	152	152	154	[illegible]	149	146	144	R	
6	F				21	21	26	22	26	25	26	25	25	25	28	30	30	29	28	28	28	25			F	6
	R				132	142	159	160	157	154	151	152	151	151	152	153	153	152	153	153	153	152			R	
4	F				21	25	26	26	26	26	26	25	26	25	28	28	28	28	29	28					F	4
	R				132	139	150	157	157	155	153	154	155	150	158	153	154	154	155	155					R	
2	F					25	26	26	22	24	25	25	26	25	27	28	28	28							F	2
	R					140	150	154	157	154	158	153	153	152	154	154	153	155							R	
1	F					25	24	23	25	24	25	25	25	25	27	27	29								F	1
	R					140	147	154	153	155	153	153	153	152	154	154	152								R	
AD CL																										
BT CL																										

69.54% within ± 5° of 30/150°

FILAMENT WOUND SHIP HULL

LRY WIND-REVIEW 42-140 [illegible]

PROGRAM 33-FE-30"

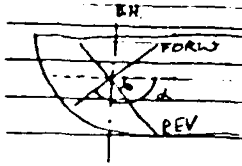
Winding Angles (6-9-83) THURSDAY

SKIN EXPANSION

STATION LINE →
WATER LINE ↓

PORT SIDE
(LEFT)

BH



F=α R=θ

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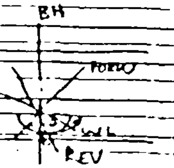

WL		-1	-1/2	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20		
24	R			28	27	29	30	31	33	34	34	34	34	34	34	31	34	33	30	32					R	24
	F			118	126	134	140	146	150	152	150	150	148	143	146	140	146	148	146	147					F	
20	R	-	-	28	27	29	29	30	32	34	34	34	34	34	31	34	34	33	30	32	33	33	40	45	R	20
	F			118	126	134	141	148	152	152	150	150	148	148	146	146	146	146	140	147	147	146	140	145	F	
MD																										
16	R	-	-	53	27	27	29	30	32	33	34	34	35	34	34	34	33	33	33	32	33	35	40	45	R	16
	F			112	132	138	146	146	152	152	150	150	147	146	147	142	146	146	141	147	147	146	146	147	F	
14	R			53	33	27	29	30	31	32	34	34	35	34	34	33	34	33	33	33	33	36	40	50	R	14
	F			122	134	138	150	149	152	152	150	149	147	146	147	146	[illegible]	146	147	148	148	148	145	147	F	
12	R			66	33	2[illegible]	29	30	31	32	34	34	33	34	34	35	34	35	32	33	33	40	40	50	R	12
	F			123	134	142	150	149	152	152	150	149	148	146	147	146	146	148	148	148	147	150	145	147	F	
10	R			26	41	25	28	28	31	32	32	34	33	34	35	35	31	33	32	36	33	40	47	52	R	10
	F			131	138	144	150	150	152	150	150	149	148	148	147	146	148	148	148	150	150	150	150	150	F	
8	R			-	41	26	27	28	26	30	32	32	33	34	35	33	30	30	30	30	33	38	44	52	R	8
	F				138	146	150	150	150	150	148	147	148	148	147	146	148	148	148	150	150	150	150	150	F	
6	R				47	37	2[illegible]	27	26	30	32	32	32	34	34	33	29	29	30	30	33	35			R	6
	F				143	148	150	150	150	150	148	147	148	149	152	146	148	150	148	150	151	154	-		F	
4	R				27	30	25	27	26	30	29	30	32	34	32	32	30	29	30	30					R	4
	F				147	150	150	150	152	150	150	149	148	149	148	147	150	150	150	150					F	
2	R					37	27	27	26	27	29	30	31	32	30	33	30	30							R	2
	F					150	150	152	152	150	150	150	149	150	151	148	150	150							F	
1	R					37	27	22	25	28	28	30	31	32	30	30	30								R	1
	F					150	150	148	152	152	[illegible]	150	149	150	[illegible]	151	150								F	
MD CL																										
87 CL																										

811% within ±5° at 20°

APPENDIX B.1

PROPOSED MATERIAL REQUIREMENTS FOR FILAMENT WINDING A 30 FT MODEL SHIP HULL

1.0 SCOPE

1.1 Scope. This document covers the reinforcement and matrix resin materials to be used in the filament winding of a 30 ft modelship hull.

1.2 Classification. Not Applicable

2.0 Reinforcements.

2.1 Glass Roving. The glass roving used in the fabrication of this model shall conform to the requirements of MIL-R-60346, Type I, Class 2.

2.2 Glass Cloth. E Glass cloth used in areas of reinforcement or for surface finish on the filament wound hull shall conform to the requirements of MIL-C-9084, Class 1.

2.3 Kevlar Roving. Kevlar roving, if used, shall conform to the requirements of AMS 3901. Size or finish on the roving shall be compatible with polyester (vinyl ester) resin.

2.4 Kevlar Cloth. Kevlar cloth, if used as a surface reinforcement, shall conform to the requirements of AMS 3902. Size or finish shall be compatible with polyester (vinyl ester) resin.

3.0 Matrix Resin. The matrix resin, whether polyester or vinyl ester, shall meet the requirements of the "Proposed Requirements Document" included in this Appendix (B.2). It is intended that this requirement could be used for both the model and eventually a ship hull winding. It is basically a restatement of the requirements in MIL-R-7575, in order to be compatible with unidirectional filament lamination.

4.0 Process Requirements. The "Proposed Process Requirement" for Filament Winding the 30 ft Hull Model is included in this Appendix (B.3) to the report. It is intended as a preliminary guide, and is subject to revision during the developemnt of the model hull.

APPENDIX B2

PROPOSED REQUIREMENTS FOR:
RESIN, FILAMENT WINDING, ROOM
TEMPERATURE CURING

1.0 SCOPE

1.1 Scope. This document covers the requirements for a room temperature curing resin to be used in the fabrication of large and thick, glass and Kevlar roving reinforced, filament wound composite articles for marine use.

1.2 Classification. Resins complying to this requirement shall be of the classifications listed below:

1.2.1 Type. Type refers to the chemical structure of the resin covered by this requirement:

I. Polyesters

II. Vinyl esters

1.2.2 Classes. The following classes of resin are covered by this requirement:

1. Normal

2. Fire Retardant

2.0 APPLICABLE DOCUMENTS:

2.1 Government Documents. The following Government documents form a part of this requirement to the extent specified herein. Unless otherwise indicated, the issue in effect on the date of invitation for bids shall apply.

SPECIFICATIONS

Military

MIL-R-7575	Resin, Polyester, Low Pressure Laminating.
MIL-R-21607	Resins, Polyester, Low Pressure Laminating, Fire-Retardant.
MIL-R-60346	Roving, Glass, Fibrous (For Prepreg, Tape and Roving, Filament Winding, and Pultrusion Applications).

STANDARDS

Federal

FED-STD-406	Plastics: Methods of Testing

(Copies of Government specifications required by suppliers in connection with specific procurement functions should be obtained from:
Commanding Officer, Naval Publications and Forms Center,
5801 Tabor Avenue
Philadelphia, PA 19120).

2.2 Non-Government Documents. The following non-government documents form a part of this requirement to the extent specified herein. Unless otherwise indicated in the listing, the latest issue in effect shall apply.

SPECIFICATIONS

American Society for Testing and Materials

ASTM D 256	Impact Resistance of Plastics and Electrical Insulating Materials, Standard Test Method for
ASTM D 648	Deflection Temperature of Plastics Under Flexural Load, Standard Test Method for
ASTM D 792	Specific Gravity and Density of Plastics by Displacement, Standard Test Method for
ASTM D 1505	Density of Plastics by the Density-Gradient Technique, Standard Test Method for
ASTM D 2290	Apparent Tensile Strength of Ring or Tubular Plastics and Reinforced Plastics by Split Disk Method, Standard Test Method for
ASTM D 2291	Fabrication of Ring Test Specimens for Glass-Resin Composites, Standard Recommended Practices for
ASTM D 2344	Apparent Interlaminar Shear Strength of Parallel Fiber Composites by Short-Beam Method, Standard Test Method for
ASTM D 2393	Viscosity of Epoxy Resins and Related Components, Standard Test Method for
ASTM D 2471	Gel Time and Peak Exothermic Temperature of Reacting Thermosetting Resins, Standard Test Method for
ASTM D 2583	Indentation Hardness of Rigid Plastics by Means of a Barcol Impressor, Standard Test Method for
ASTM D 2734	Void Content of Reinforced Plastics, Standard Test Method for
ASTM D 2849	Urethane Foam Polyol Raw Materials, Standard Methods of Testing
ASTM D 3039	Tensile Properties of Fiber-Resin Composites, Standard Test Method for

(Applications for copies should be addressed to:
American Society for Testing and Materials,
1916 Race Street
Philadelphia, PA 19103).

3.0 REQUIREMENTS:

3.1 Materials. The product furnished under this specification shall consist of a room-temperature curing polyester or vinyl ester resin system and, in separate containers, catalysts and promoters of three basic types:

- Organic Peroxides, e.g., Methyl Ethyl Ketone Peroxide (MEKP);
- Organometallic Salts, e.g., Cobalt Naphthenate (Conap); and
- Organic Tertiary Amines, e.g., Dimethylaniline (DMA).

3.2 Form and Workmanship. The resin, catalyst and promoters furnished to this requirement shall be free of impurities and any additives which would detract from the intended performance of the cured resin system under this requirement. Such additives included, but are not limited to, thixatropes, dyes and colorants, and non-reactive viscosity modifiers. Only resins purchased to the Class 2 flammability standard of this requirement shall contain any suspended solid, so long as this suspension is required for the attachment of that standard.

3.3 Neat Resin Properties. Properties of the as-received neat resin and cured neat resin shall be as shown in Tables I and II. The resin, catalysts and promoters are stored separately in sealed containers prior to test.

TABLE I

NEAT RESIN PROPERTIES

Physical Property Test	Unit	Value	Type	Class
Color	Gardner, Max.	2 5	I II	1 only 1 only
Specific Gravity	--	Report	Both	Both
Viscosity	Poise	5 - 10 2.5 - 10	I II	Both Both
Acid Number	--	Report	Both	Both
Gel Time (R.T.)*	Minutes	Report	Both	Both
Peak Exotherm (R.T.)*	Minutes	Report	Both	Both

* Catalyzed.

TABLE II

CURED NEAT RESIN PROPERTIES

Property Test	Units	Value	Type	Class
Specific Gravity	--	Report	Both	Both
Volume Shrinkage	Percent, Maximum	8 9	I II	Both Both
Hardness	Barcol, Minimum	40 35	I II	Both Both
Heat Distortion Temperature (264 psi)	°F, Minimum	200 170	I II	Both Both
Solvent Digestion	Weight Percent, Maximum	2	Both	Both

3.4 Gel Time and Time to Cure Exotherm. By use of the catalysts and promoters, described above, in the correct ratios; the resin gel time and the time to cure exotherm can be adjusted for a considerable span of time for both classes of resins. This is required so that large bulk quantities of the filament wound resin do not begin to uncontrollably exotherm during the winding process. An elevated temperature postcure of no greater than 150°F is permitted to complete the cure.

3.5 Storage Life. Storage life of the resin shall be at least three months from the date of receipt when stored, sealed and uncatalyzed, at temperatures between 50°F and 75°F.

3.6 Glass Reinforced Resin Properties.

3.6.1 Glass Reinforced Filament Wound Flat Test Panels. The unidirectionally reinforced composite, wound onto a mandrel containing a minimum of two flat surfaces, each a minimum of 6 inches wide and twelve inches long (fiber direction), shall provide specimens possessing the properties as listed in Table III.

TABLE III

PHYSICAL & MECHANICAL PROPERTIES OF FILAMENT WOUND FLAT PANELS

Property Test	Units	Value	Type	Class
Fiber Volume	Volume Percent	60 ± 7	Both	Both
Void Volume	Volume Percent, Maximum	3	Both	Both
Laminate Density	g/cm^3	Report	Both	Both

TABLE III (Continued)

Property Test	Units	Value*	Type	Class
Longitudinal Tensile				
Strength	Psi, min.	180,000 160,000	I II	Both Both
Modulus	Msi, min.	5.0	Both	Both
Strain to Failure	Percent Minimum	1.6 3.2	I II	Both Both
Longitudinal Flexural				
Strength	Psi, min.	100,000 180,000	I II	Both
Short Beam Shear				
Strength	Psi, min.	4,500 5,500	I II	Both Both

* A minimum of four specimens per average value shall be run. A specimen value of less than 90% of the average shall result in retest.

3.6.2 Thick Glass Reinforced Filament Wound Test Sections. The resin, when catalyzed and filament wound with E-glass reinforcement onto a mandrel containing a flat surface at least 6 inches long by 6 inches wide, shall have the properties as shown in Table IV.

TABLE IV

PHYSICAL & MECHANICAL PROPERTIES OF FILAMENT WOUND THICK SECTIONS

Property Test	Units	Value	Type	Class
Fiber Volume	Volume Percent	60 ± 7	Both	Both
Void Volume	Volume Percent, Maximum	3	Both	Both
Laminate Density	g/cm^3	Report	Both	Both
Izod Impact Strength	ft-lb/in,	Report Report	I II	Both
Flame Resistance				
Ignition Time	Seconds, Minimum	55 70	Both Both	1 2
Burning Time	Seconds, Minimum	125 65	Both Both	1 2

3.6.3 Glass Ring Test Specimens. The resin, when catalyzed and filament wound, using E-glass reinforcement, into "NOL" rings shall have the properties listed in Table V.

TABLE V

CURED PHYSICAL & MECHANICAL PROPERTIES OF FILAMENT WOUND GLASS RINGS

Property Test	Units	Value	Type	Class
Fiber Volume	Volume Percent	60 ± 7	Both	Both
Void Volume	Volume Percent	3	Both	Both
Laminate Density	g/cm^3	Report	Both	Both
Apparent Tensile Strength	psi	80,000 160,000	I II	Both Both
Short Beam Shear Strength	psi	4,500 5,500	I II	Both Both

3.7 Wet Testing. Mechanical properties of those specimens tested wet shall be reduced no more than 10% from the dry values recorded above. Moisture pickup of the composite specimens shall be no greater than 0.5% for all classes and types of resin considered herein.

3.8 Weatherability. The mechanical properties of those specimens tested after one year of weathering shall be 90% of their dry values. Physical properties shall be within 1% of the initial values.

4.0 QUALITY ASSURANCE PROVISIONS:

4.1 Classification of Examinations and Tests. The examination and testing of the neat resin and E-glass reinforced composite windings prepared from this resin shall be classified as follows:

4.1.1 Qualification Tests. Qualification tests, as listed in Table VI, shall be performed to enable the procuring agency to determine the material complies with this requirement. The qualification shall consist of all examinations and tests included in Section 4 except as otherwise noted.

4.1.2 Quality Conformance Tests. Quality conformance tests and examinations, as listed in Table VI, shall be performed on individsual lots of products submitted for acceptance.

AD-A134 577 FILAMENT WINDING OF A SHIP HULL A STUDY OF THE DESIGN OF A 30 FT FILAMENT..(U) LOCKHEED MISSILES AND SPACE CO INC SUNNYVALE CA ADVANCED MARI.. D N CHAPPELEAR ET AL. 3/3

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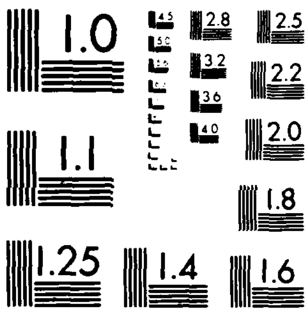

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963 A

TABLE VI

EXAMINATIONS AND TESTS

Examination or Test	Requirement	Test Method	Qualification	Quality Conformance
Color	Table I	4.2.1	X	X
Specific Gravity	Table I	4.2.2	X	
Viscosity	Table I	4.2.3	X	X
Acid Number	Table I	4.2.4	X	
Gel Time	Table I, 3.4	4.2.5	X	X
Time to Peak Exotherm	Table I, 3.4	4.2.5	X	X
Solvent Digestion	Table II	4.3.1	X	
Heat Distortion Temp.	Table II	4.3.2	X	
Specific Gravity	Table II	4.3.3	X	X
Hardness	Table II	4.3.4	X	X
Volume Shrinkage	Table II	4.3.5	X	
Workmanship	3.2	4.4	X	X
Storage Life	3.5	4.5	X	
Fiber Volume	Tables III, IV, V	4.6.2.1, 4.6.5 4.6.5.1	X	X
Void Volume	Tables III, IV, V	4.6.2.1, 4.6.5 4.6.5.1	X	X
Laminate Density	Tables III, IV, V	4.6.2.3, 4.6.5 4.6.5.1	X	X
Longitudinal Tensile Strength	Table III	4.6.3.1	X	
Modulus	Table III	4.6.3.1	X	
Strain-to-Failure	Table III	4.6.3.1	X	
Longitudinal Flexural Strength	Table III	4.6.3.2	X	
Short Beam Shear Strength	Tables III, V	4.6.3.3 4.6.5.2	X	X
Flame Resistance	Table IV	4.6.4.1	X	
Izod Impact	Table IV	4.6.4.2	X	
Apparent Tensile Strength	Table V	4.6.5.1		X
Wet Testing	3.7	4.7	X	
Weatherability	3.8	4.8	X	

4.2 Tests on As-Received, Uncatalyzed Resin.

4.2.1 Color. Color of the resin shall be measured by the Gardener color method as described in ASTM D 2849 under COLOR.

4.2.2 Specific Gravity. Specific gravity of the resin shall be determined in the same manner as it is for polyester resins in MIL-R-7575.

4.2.3 Viscosity. Viscosity of the resin shall be measured by a Brookfield viscometer to ASTM D 2393 using spindle no. 2 at 20 rpm.

4.2.4 Acid Number. Acid number shall be determined by the method outlined in MIL-R-7575.

4.2.5 Gel Time and Time to Peak Exotherm. These values along with peak exotherm temperature shall be determined according to ASTM D 2471. Fifty g of resin shall be catalyzed with 1.25% MEKP at 77°F for the running of the baseline.

4.3 Tests on Cured Neat Resin. The neat resin is cured in molds of sufficient size to generate the necessary specimens required in the following paragraphs. Cure shall be 24 hrs minimum at room temperature followed by an optional thermal postcure of no more than 150°F.

4.3.1 Solvent Digestion. A 10g or less casting is dried and accurately weighed to the nearest 0.001g (W_1). The specimen is then immersed in refluxing acetone for 30 minutes, rinsed with fresh acetone, removed, patted dry, and placed in a preset 250°F oven for 30 minutes. The specimen is then allowed to cool in a desiccator to ambient temperature and reweighed (W_2). Weight loss in percent is calculated from the following equation:

$$\text{Weight Loss} = \frac{W_1 - W_2}{W_1} \; (100\%)$$

4.3.2 Heat Distortion Temperature. The heat distortion temperature of the cured resin system shall be measured according to the provisions contained in ASTM D 648.

4.3.3 Specific Gravity. The specific gravity of the cured resin shall be measured either according to the provisions of ASTM D 792 or ASTM D 1505.

4.3.4 Hardness. The hardness of the cured resin shall be measured according to the provisions contained in ASTM D 2583.

4.3.5 Volume Shrinkage. This value is calculated from the specific gravities of the liquid and the cured solid resin (s.g.ℓ and s.g.c respectively) by the following equation:

$$V_s = \frac{s.g.c - s.g.\ell}{s.g.c} \; (100\%)$$

4.4 Workmanship. The material shall be tested for conformance to the workmanship requirements of 3.2. Use shall be made of chemical instrumentation such as infrared spectrometers and high-pressure liquid chromatography to assist in the determination of compliance to these requirements.

4.5 <u>Storage Life.</u> The resin shall meet the requirements listed in this specification three months after receipt from the vendor provided it has been stored in closed containers prior to this point in time and that these containers have been stored out of direct sunlight at a temperature of 50°F to 75°F.

4.6 <u>Tests on Filament Wound Glass Reinforced Coupons.</u>

4.6.1 <u>Qualification Tests.</u> A total of two windings are made. In the first, glass reinforced resin is wound unidirectionally about a mandrel containing at least two flat sections each of which has a minimum area of 6 inches wide by 12 inches long. The thickness of the unidirectional glass reinforced composite shall be 0.125 ± 0.005 inches. To insure no residual stress, the winding shall be cut from the mandrel prior to cure completion. Cure shall be twenty-four hours at room temperature followed by a thermal postcure of no higher than 150°F.

The second winding is wound with glass reinforced resin about a mandrel containing at least one flat section with a minimal area of 6 inches by 6 inches. The thickness of the glass reinforced composite shall be, as a minimum, 0.625 inches. Cure and postcure shall be the same as above. The winding need not necessarily be unidirectional for this part but should be consistent from part to part. The glass used in these windings shall be: E-glass conforming to MIL-R-60346, Type I, Class 2.

4.6.2 <u>Tests Conducted on Both Windings.</u>

4.6.2.1 <u>Fiber Volume.</u> Fiber volume shall be determined in accordance with method 7061 of FED-STD-406 on three separate samples except that the numbers obtained will be used to solve the following equation:

$$\text{Fiber, Volume \%} = [(W/F)/(W/C)] \times 100$$

Where: W = Weight of fabric in the composite;
F = Density of E-glass (2.540 g/cm^3);
W = Weight of the initial composite specimen;
C = Composite density from 4.4.4.1.

4.6.2.2 <u>Void Volume.</u> A minimum of three individual values shall be obtained in accordance with ASTM D 2734, Methods A or B.

4.6.2.3 <u>Laminate Density.</u> A minimum of two individual tests shall be run in accordance with either ASTM D 792 or ASTM D 1505.

4.6.3 <u>Tests Conducted on the 0.125 inch Thick Flat Winding.</u>

4.6.3.1 <u>Tensile Testing.</u> Tensile testing shall be to ASTM D 3039. Five samples shall be tested for strength modulus and strain to failure in the longitudinal direction at room temperature.

4.6.3.2 <u>Flexural Testing.</u> Flexural testing shall be per FED-STD-406, Method 1031. Five coupons shall be tested for strength.

4.6 <u>Short Beam Shear Strength.</u> Five specimens shall be tested to ASTM D 2344.

4.6.4 <u>Tests Conducted on the 0.625 inch Thick Winding.</u>

4.6.4.1 Flame Resistance. Flame resistance shall be measured to Method 2023 of FED-STD-406. Five specimens shall be tested. The ignition time and burning time shall be calculated according to the equations in MIL-R-21607.

4.6.4.2 Izod Impact Test. Impact test specimens shall be fabricated to the dimensions given in ASTM D 256, Method A.

4.6.5 Quality Conformance Tests. Six E-glass reinforced ring test specimens shall be fabricated to the requirements of ASTM D 2291. As above, the cure for these articles shall be 24 hours minimum at room temperature followed by a thermal postcure of no greater than 150°F. Fiber volume, void volume and laminate density shall be determined from one ring to the provisions in 4.6.2 above.

4.6.5.1 Apparent Tensile Strength. Five of the rings prepared above shall be tested according to the provisions in ASTM D 2250 to determine the apparent tensile strength of the glass reinforced resin. Samples for fiber volume, void volume and laminate density shall be taken from at least two of these failed specimens.

4.6.5.2. Short Beam Shear Strength. One ring prepared above shall have five specimens cut from it and tested for apparent interlaminar shear strength to the provisions of ASTM D 2344.

4.7 Wet Testing. Coupons from 0.125 inch thick windings prepared to the provisions of 4.6.1 shall be subjected either to immersion for two hours in boiling distilled water per Method 7031A of FED-STD-406 or preferrably for 30 days in distilled water at 23 ± 1°C per MIL-R-7575. Immediately after removal, the specimens are tested at room temperature. Moisture pickup shall be measured by weighing a given sample before and after testing.

$$M = \frac{W_A - W_B}{W_B} = (100\%)$$

Where: M = Percent moisture pickup
W_A = Weight of sample after.
W_B = Weight of sample before.

4.8 Weatherability. 0.125 inch thick windings shall be exposed to the weather conforming to those conditions listed in MIL-R-21607. Mechanical properties of specimens cut from these windings shall then be measured at room temperature. In addition fiber volume, void volume and laminate density shall be measured.

APPENDIX B3

PROPOSED PROCESS REQUIREMENTS FOR WET, TWO-POT, FILAMENT WINDING OF A PRIMARILY E-GLASS ROVING REINFORCED 30 FOOT SHIP HULL

1.0 SCOPE:

1.1 Scope. This document covers the requirements for wet, two-pot filament winding a 30 foot ship hull using primarily E-glass roving reinforcement and a room temperature curing polyester or vinyl ester matrix resin system.

1.2 Classification. Not applicable.

2.0 APPLICABLE DOCUMENTS:

2.1 Government Documents. The following Government documents form a part of this requirement to the extent specified herein. Unless otherwise indicated, the issue in effect on the date of invitation for bids shall apply.

SPECIFICATIONS

Military

MIL-C-9084	Cloth, Glass, Finished, for Resin Laminates.
MIL-M-43243	Mats, Reinforcing, Glass Fiber.
MIL-R-60346	Roving, Glass, Fibrous (For Prepreg Tape and Roving, Filament Winding, and Pultrusion Applications).

STANDARDS

Federal

FED-STD-406	Plastics: Methods of Testing.

(Copies of Government specifications required by suppliers in connection with specific procurement functions should be obtained from:
Commanding Officer, Naval Publications and Forms Center,
5801 Tabor Avenue
Philadelphia, PA 19120).

2.2 Non-Government Documents. The following non-government documents form a part of this requirement to the extent specified herein. Unless otherwise indicated in the listing, the latest issue in effect shall apply.

SPECIFICATIONS

American Society for Testing and Materials.

ASTM D 792	Specific Gravity and Density of Plastics by Displacement, Standard Test Method for.
ASTM D 1505	Density of Plastics by the Density-Gradient Technique, Standard Test Method for.

ASTM D 2583	Indentation Hardness of Rigid Plastics by Means of a Barcol Impressor, Standard Test Method for.
ASTM D 2734	Void Content of Reinforced Plastics, Standard Test Method for.
ASTM D 3039	Tensile Properties of Fiber-Resin Composites, Standard Test Method for.

(Applications for copies should be addressed to:
American Society for Testing and Materials,
1916 Race Street
Philadelphia, PA 19103).

Society of Automotive Engineers, Inc.

AMS 3901	Organic Fiber, Yarn and Roving, High Modulus, for Structural Composites.
AMS 3902	Cloth, Organic Fiber, High Modulus, for Structural Composites.

(Applications for copies should be addressed to:
Society of Automotive Engineers, Inc.,
400 Commonwealth Drive
Warrendale, PA 15096).

OTHER DOCUMENTS

Lockheed Missiles and Space Company

Proposed Requirements for Resin, Filament Winding, Room Temperature Curing.

3.0 REQUIREMENTS:

3.1 Qualification. Not applicable.

3.2 Materials.

3.2.1 End-Item Materials. End-item identifiable materials are those materials used in this specification that retain their identity throughout processing and form a part of the end-item hardware. A partial list of end-item identifiable material includes the matrix resin and the woven cloth or roving reinforcement.

3.2.2 Process Consumable Materials. Process consumable materials may be used in the performance of the process but do not become identifiable constituents of the end-item part.

3.3 Equipment. All equipment used in this process shall have been accepted for manufacturing production and shall bear current instrumentation calibration.

3.3.1 **Filament Winding Equipment.** The filament winding machine shall be any of a lathe type multiaxis variety in which the fiber direction can be programmed onto a computer through a set number of sequences to repeat after a given number of passes. The machine shall be equipped with a given number of bobbins of such design that roving bought to specification shall fit without rewinding. The bobbins shall be arranged so that one half of the roving strands from the spools shall pass through one resin pot and the other half through a second resin pot. The strands of roving shall be combined at the eye in such a manner that every other roving strand shall have gone through the same pot. In this manner the resins placed in the pots will intermingle with each other as they reach the mandrel facilitating as even as possible a mixture and as uniform as possible a cure of the resin from the two pots.

3.3.2 **Mandrel.** The mandrel shall be prepared from a material stiff enough to be wound upon without distortion either from the effects of gravity or from winding tension. It shall be of such design and construction that it can be removed from the inside of the part with a minimum of effort. Suggested materials for mandrels include:

- Salt - Steel;
- Plaster - Steel;
- Tooling Resin - Steel;
- Structural Foam - Steel;
- Aluminum Plate - Steel.

In all of the above cases, the mandrel will be built about a steel shaft which will, in turn, be inserted into the chuck of the filament winding machine. In the case of salt and plaster mandrels, the shaft is broken loose and removed and the plaster or salt is chipped or washed. Such mandrels, therefore, are for one-of-a-kind items only. The tooling resin and aluminum plate mandrels are built up in sections and, once the steel shaft has been removed, can be disassembled from the cured part and then reassembled for the next part. The structural foam can be used in both methods of manufacture.

3.3.4 **Thermocouples.** The mandrel shall be designed so that thermocouple leads can be attached. These thermocouples will be placed near the mandrel surface so that the exotherm temperature of the part as it cures can be monitored.

3.3.5 **Facilities.** Winding shall be performed in an area which is subjected to a periodic cleaning schedule. No eating, smoking or drinking shall be allowed within this area. No grinding, sawing or sanding shall be allowed during the preparation for and actual winding of the model.

3.4 **Process Operation.**

3.4.1 **Materials.**

3.4.1.1 **Resin Life.** The resin must be within storage and work time life limitations at the time of the winding.

3.4.1.2 **Catalysts.** Catalysts and promoters should be fresh, within work time life and capable of curing the resin to the proscribed degree within a proscribed period of time as defined in the materials specification for the matrix resin.

3.4.1.3 Roving. The roving must be treated with the correct size for the resin applied. If the size is of a finite lifetime, the roving must be within storage and worklife limitations at the time of winding. The roving should be packaged so that the fibers remain unbruised prior to use and so that the spools can be placed directly on the holders of the winding machine without respooling.

3.4.2 Winding.

3.4.2.1 Dry Winding. Prior to the actual winding of the ship hull, winding of dry fiber onto the mandrel shall be undertaken to determine the number of different types of passes and their winding angle that have to be employed. This data, once obtained and optimized shall be fed into the computer used to control the filament winding operation. Pins may be needed to maintain the fiber direction onto the mandrel during this dry, winding procedure.

3.4.2.2 Wet Winding. The resin system considered for filament winding of the model should have gel times which can be adjusted from a few minutes to several hours. Thus for good interply adhesion the winding process, once it begins, shall not be shut down for any length of time (TBD) until the part is completely wound. The catalyst and promoter concentration shall be used to govern the resin gel time. At the commencement of the winding procedure, the gel time shall be set to be fairly rapid to insure that the part begins to exotherm when it is relatively thin early in the winding procedure so that it does not begin to decompose from too much heat. Once exotherm has commenced the amount of catalyst and promoters can be reduced to "cool" the system so that the winding below the one being wound is never fully cured. At this point, if possible, it would be advantageous to go with a one-pot system.

3.4.2.3 High Modulus Roving Reinforcement. It may be advantageous to wind Kevlar reinforcement in a longitudinal direction about the hull. ~~At this~~ point one set of bobbins may have the glass replaced with Kevlar roving. Kevlar may be wound first from this one set of bobbins using one pot or intersperced with glass roving from the second set of bobbins using both pots.

3.4.3 Wet Hand Lay-up.

3.4.3.1 Glass Fabric Reinforcement. Glass fabric reinforcement using wet resin matrix is scheduled to be used in certain areas of the model where winding may lead to fiber slippage or bridging. The fabric will be cut to size, wet with resin and quickly squeezed into place on the part. Filament winding will then be resumed to the hand layed up article to the filament wound structure. This process may be repeated as often as desired to build up areas which require reinforcement or areas weakened by their inability to be conveniently reached by filament winding.

In addition sections of the model, notably the bowsprit and the stern shall be hand layed up from glass fabric, cured, cut to size, and bonded to the filament wound hull.

3.4.3.2 Kevlar Fabric Reinforcement. Kevlar fabric may be used as a reinforcement for those areas due to receive considerable amounts of wear. As this is a model such areas probably would not exist. Never-the-less proposed deck areas, etc., for a full-sized vessel would be given one or two plies of Kevlar fabric, wet layed as the final or next-to-final plies for these areas. This does not include sacrificial plies (below).

3.4.4.1 Cure. Cure shall be 24 hours minimum at room temperature.

3.4.4.2 Postcure. Postcure shall be thermal and by heat lamps. The resin shall develop its full mechanical potential utilizing a postcure temperature of no greater than 150°F.

3.4.5 Finishing Operations.

3.4.5.1 Sacrificial Plies. Sacrificial windings or wet mat layup may be used so that the craft upon sanding and gel coat shall have a smooth symmetrical center surface.

3.4.5.2 Bowsprit and Aft Section. The bowsprit and aft section shall be wet hand layed up separately and attached to the filament wound hull section after cure and removal of the mandrel. Type of attachment is TBD.

3.4.5.3 Paint. Hull painting of the model is TBD.

3.4.6 Tag End Specimen. All testing will be done from tag end specimen cut from the wound part as hatchways, etc., and from the hand layed parts.

3.4.6.1 Tag-End Specimen Dimensions. Dimensions of the tag-end specimens are TBD and depend on the size of the openings etc., required by the engineering drawing.

3.4.6.2 Properties of the Tag-End Test Panel. Individual specimen minimum mechanical properties shall conform to the requirements of Table I. The mechanical values in this Table are based on a polyester matrix composite wrapped in a pseudo-isotropic layup $(0/45/90/135)_S$ and will change (increase) if a vinyl ester resin is substituted. These values will also change if a different winding pattern is employed or if Kevlar is used in the layup.

3.5 Workmanship.

3.5.1 Appearance. The finished model shall be of uniform color and regular appearance. The hull surface shall be smooth, uniform and free from resin starved areas and similiar defects. The E model shall be symmetrical about a plane through the bow and stern along the centerline. There shall be not gross void or blistered areas due to bridging, etc., of the filament wound portion.

3.5.2 Cracks. There shall be no visible cracks (actual fractures) in any part of the surface.

3.5 3 Resin Removal or Addition. Hand finishing and machining shall be permitted to remove resin rich or wrinkled areas provided this operation does not penetrate the sacrificial plies layed on for just such a purpose.

3.5.4 Fiber Volume and Void Volume. Fiber volume and void volume shall be as shown in Table I.

3.5.5 Thickness. The model thickness shall conform to the thickness requirements of the engineering drawing.

TABLE I

PROPERTIES OF TAG-END SPECIMENS FROM FILAMENT WOUND SHIP MODEL

Property	Requirements	Number Specimens	Test Method
Hardness	Barcol TBD minimum	6	ASTM D 2583
Density	Report	3	ASTM D 792, ASTM D 1505
Solvent Digestion	2 percent maximum	3	Refluxing Acetone
Fiber Volume	60 ± 10 volume percent	3	FED-STD-406, method
Void Volume	3 percent maximum	3	ASTM D 2734
Tensile Strength	40,000 psi minimum average	5	ASTM D 3039
Flexural Strength	45,000 psi minimum average	5	FED-STD-406, method 1031
Flexural Modulus	2.7 Msi minimum average	5	FED-STD-406, method 1031
Edgewise Compressive Strength	35,000 psi minimum average	5	FED-STD-406, method 1021

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